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EVALUATION OF ASPHALT RUBBER BINDERS IN POROUS FRICTION COURSES

by

Gary L. Anderton

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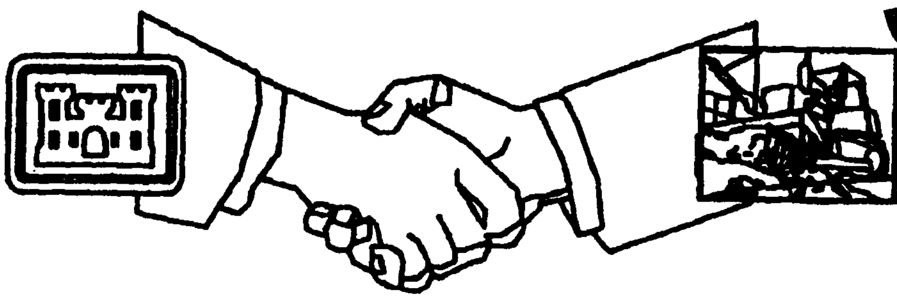

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

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13. ABSTRACT *(Maximum 200 words)*

This report documents a laboratory research effort to determine the potential benefits of asphalt rubber binders when used in porous friction courses. The results of this research study are also used to recommend the asphalt cement grades and mix design procedure required to achieve optimum field performance.

This study was conducted as part of a joint research project between the US Army Corps of Engineers and the Asphalt Rubber Producers Group (ARPG) under the Corps' Construction Productivity Advancement Research (CPAR) program. Other CPAR research studies relating to asphalt rubber pavement systems were conducted under ARPG contracts and are documented separately from this report.

The laboratory tests conducted at the US Army Engineer Waterways Experiment Station included physical tests on various grades of asphalt rubber and asphalt cement binders. Accelerated aging tests were conducted on the binders to determine short- and long-term aging tendencies. A mix design analysis and several physical tests were conducted on open-graded mixtures containing the asphalt rubber binders.

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The results of this study indicated that porous friction courses made with asphalt rubber binders would be more durable, longer lasting, and better water draining pavement layers when compared with unmodified asphalt cement porous friction courses. Asphalt cement grades between the AC-5 and AC-20 viscosity grades are recommended for use in asphalt rubber binder systems. A generalized mix design method for designing asphalt rubber porous friction course mixtures is presented in the appendix of this report.

14. (Concluded).

Porous friction course
Recycling
Skid resistance

PREFACE

This study was conducted by the Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for the US Army Corps of Engineers (USACE) under the Construction Productivity Advancement Research (CPAR) Program. The work was conducted from October 1989 to September 1991 under the project entitled "Asphalt Rubber". The USACE Technical Monitor was Mr. Paige Johnson.

The laboratory evaluation summarized in this report was part of a joint research program which was equally funded by the USACE CPAR program and the Asphalt Rubber Producers Group (ARPG). USACE funds were used to support the research conducted by WES, and ARPG funds were used to support the research conducted by various academic and industry agencies including the University of Nevada-Reno, the University of Arizona, Crafco, Inc., and International Surfacing, Inc.

The study was conducted under the general supervision of Dr. W. F. Marcuson III, Director, GL; Mr. H. H. Ulery, Jr., former Chief, Pavement Systems Division (PSD); and Mr. T. W. Vollor, Chief, Materials Research and Construction Technology Branch, PSD. This report was prepared under the direct supervision of Dr. G. M. Hammitt III, Chief, PSD. PSD personnel engaged in the laboratory testing included Messrs. B. Dorman, J. Duncan, R. Graham, H. McKnight, D. Reed, and J. Simmons. The project's Principal Investigator was Mr. G. L. Anderton who also wrote this report. Mr. G. L. Cooper of ARPG, who acted as the CPAR industry partner's authorized representative, reviewed this report before publication.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

EVALUATION OF ASPHALT RUBBER BINDERS IN POROUS FRICTION COURSES

PART I: DESCRIPTION OF RESEARCH AND DEVELOPMENT PARTNERSHIP

1. In November 1989 the US Army Engineer Waterways Experiment Station (WES) and the Asphalt Rubber Producers Group (ARPG) signed a Cooperative Research and Development Agreement which marked the beginning of a 2-year joint research study on asphalt rubber. This agreement was the first one enacted within the Corps' new Construction Productivity Advancement Research (CPAR) program. The potential benefits of this developing technology for both the Federal Government and the private sector made the asphalt rubber research study perfectly suited for the CPAR program.

2. CPAR is a cost-shared research and development partnership between the Corps and the US construction industry, academic institutions, public and private foundations, nonprofit organizations, state and local governments, and other entities who are interested in construction productivity and competitiveness. CPAR is designed to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity and project costs and on Corps mission accomplishment. The CPAR program has received strong support from the US construction industry, and numerous projects have been funded since the program was initiated in 1989.

3. Individual studies of differing research areas were conducted by several agencies under this cooperative research program. These agencies included WES's Pavement Systems Division, University of Nevada-Reno, University of Arizona, Crafco, Inc., and International Surfacing, Inc. Each individual research study was designed to evaluate the critical performance related properties of asphalt rubber concrete mixtures which would in turn lead to practical design, testing, and construction guidance. This report summarizes the results obtained from the research study conducted at WES on asphalt rubber binders and their use in porous friction courses. Detailed reports of the laboratory studies conducted by the other agencies involved in

this research program were published by the industry partner (ARPG) as separate technical reports. The titles of these technical reports are listed below:

a. Comparison of Mix Design Methods for Asphalt Rubber Concrete Mixes.

b. Permanent Deformation Characteristics of Asphalt Rubber Modified and Unmodified Asphalt Concrete Mixtures.

c. Low Temperature Cracking Characteristics of Asphalt Rubber Modified and Unmodified Asphalt Concrete Mixtures.

d. Fatigue Characteristics of Asphalt Rubber Modified and Unmodified Asphalt Concrete Mixtures.

e. Tensile Creep Evaluations of Asphalt Rubber Binders.

4. In addition to these individual technical reports, a summary report was produced which consolidates the results of all of the individual research studies. This summary report is entitled "Asphalt Rubber Pavement Systems" and was published by WES and ARPG. Copies of all of the individual technical reports and the summary report may be obtained by contacting:

Asphalt Rubber Producers Group
3336 North 32nd Street
Suite 106 Phoenix, AZ 85018-6241
(Telephone: 602-955-1141)
(FAX: 602-956-3506)

PART II: INTRODUCTION

Background

5. A porous friction course (PFC) is an open-graded type of asphaltic pavement surfacing containing approximately 20 to 30 percent air voids. The typical PFC is a 1/2- to 3/4-in.* surfacing with limited structural capacity requiring a structurally sound pavement underneath it. A properly functioning PFC will absorb precipitation and provide a drainage layer for this water to be carried out to the pavement shoulder. This function significantly enhances user safety by eliminating automobile hydroplaning and increasing overall wet weather traction. When the PFC pavement is dry, the internal air voids absorb a significant amount of road noise caused by the engine and tire/pavement contact, which reduces noise pollution in areas surrounding heavily traveled pavements. Besides providing these and other benefits, a typical PFC is a relatively inexpensive surfacing material in comparison with other asphaltic materials.

6. The use of PFC's has never been widespread in the United States because of its reputed lack of durability. A considerable number of premature failures have occurred in PFC field applications throughout the years to support this reputation (Shuler 1988, White 1975). In most instances these failures have involved raveling, stripping, and/or various types of cracking due to inefficient binders. Not only are most of the failures involving PFC's premature, but also they tend to accelerate rapidly, requiring immediate maintenance or complete removal. When designed and constructed properly, a PFC delivers significant benefits to the pavement user. When designed or constructed improperly, a PFC can become a maintenance nightmare.

7. In a typical dense-graded asphalt concrete system, there exists a proportionate amount of fine aggregates which provide structural support to the load bearing larger stones of the mix. There are very few of these fine aggregates in the typical PFC gradation. Due to the lack of fine aggregates,

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 7.

the binder plays a more important role in keeping the mixture intact. Therefore, the effects of a poor binder are much more detrimental to a PFC than to a typical dense-graded asphalt mixture. Likewise, the key to a better PFC many times lies in using a better binder.

8. Because of the open void structure, the PFC binder is exposed to harmful effects of the environment throughout the thickness of the PFC layer. Exposure to direct oxidation, water stripping and freeze-thaw cycles are problems associated with PFC binders. These conditions lead to weathered, brittle binders which cause the PFC to rapidly deteriorate. A thicker film of binder on the aggregates is an obvious approach to combat many of these hazards, but this approach is limited by the associated problems of excess binder draining off of the aggregates during construction which closes the void structure and reduces the water draining capabilities of the PFC.

9. Asphalt rubber binders have several material properties which make them attractive for PFC applications. Asphalt rubber remains highly viscous in the typical PFC mix temperature range and therefore should allow a thicker film of binder without detrimental binder drain off problems. Asphalt rubber is more elastic at low temperatures in comparison with traditional asphalt cements and therefore should be less susceptible to low temperature cracking and freeze-thaw damage. Asphalt rubber binders are more resistant to oxidation because of the antioxidants and carbon black materials in the rubber. These material properties indicate that asphalt rubber PFC's would be more durable, longer lasting, and better water draining layers when compared with conventional PFC's. Finally, the use of asphalt rubber binders is attractive from an environmental standpoint since it uses a waste product (discarded automobile and truck tires) as a raw material.

10. The term "asphalt rubber", as it is used in this study, refers to a blend of ground tire rubber and asphalt cement made at elevated temperatures. The blend consists of about 15 to 25 percent ground tire rubber by total weight of the blend, which is added to the asphalt cement and allowed to react at an elevated mixing temperature before use as a pavement binder. This reaction phase involves a combined chemical and physical reaction between the asphalt cement and rubber which results in a more viscous and elastic binder containing individual rubber particles suspended throughout the binder. Asphalt rubber paving mixtures have recently been proven safe in terms of

worker exposure to toxic fumes released during mixing and construction (Rinck and Napier 1991). Recent cost data indicate that these asphalt rubber binders cost approximately two to three times more than traditional asphalt cements (Roberts et al 1989).

Purpose

11. The purpose of this research was to evaluate the effectiveness of using asphalt rubber binders in PFC's. This research provides a sound basis for using asphalt rubber binders in order to provide a more durable, cost-effective PFC. The information provided by this research has the potential to increase the volume of PFC's constructed in the future and to make these future pavements longer lasting.

Objective

12. The objectives of this research were twofold: (1) to determine the potential benefits of asphalt rubber binders when used in PFC's and (2) to recommend the asphalt cement grades and mix design procedure required to achieve optimum field performance.

Scope

13. The scope of this study included a review of available literature and existing data, a three-phase laboratory study, and an analysis of all collected data. The laboratory study included a number of binder tests and PFC mixture tests. Three different grades of asphalt cements and three different formulations of asphalt rubber binders were included in the laboratory tests in order to make a valid comparative analysis across the normal binder viscosity range. A single standard aggregate gradation was used in the PFC mixture tests. A diagram of the laboratory test plan used in this study is shown in Figure 1.

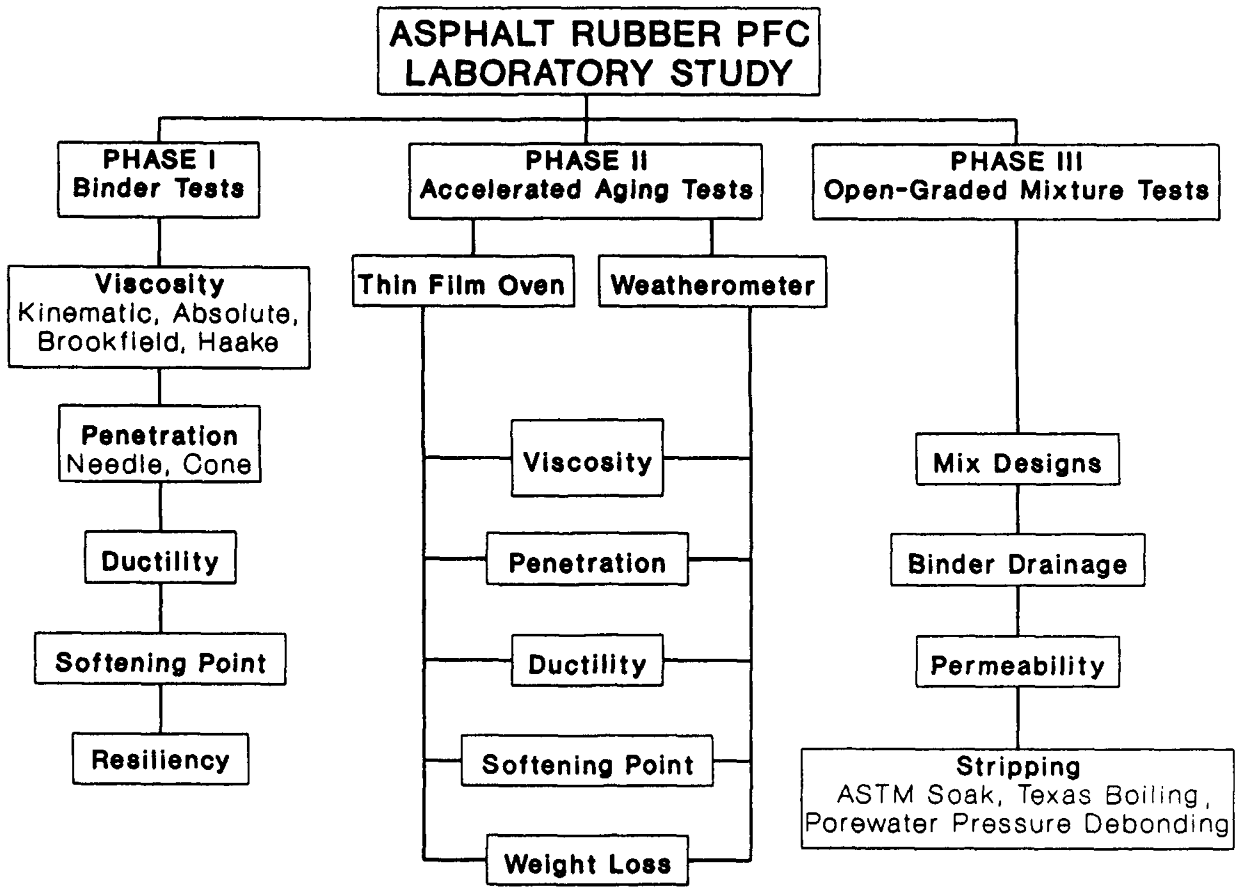

Figure 1. Flow diagram of asphalt rubber PFC laboratory study

14. The binder tests were used to determine high temperature and low temperature engineering properties so that pavement performance predictions could be made. The binder tests included:

a. Kinematic viscosity at 275°F (ASTM D2170).

b. Absolute viscosity at 140°F (ASTM D2171).

c. Brookfield viscosity at 194°F, 221°F, 250°F, 275°F (ASTM D2994).

d. Haake viscosity at 194°F, 221°F, 250°F, 275°F.

e. Penetration at 39°F, 77°F (ASTM D5).

f. Cone penetration at 39°F, 77°F (ASTM D217).

g. Ductility at 39°F, 77°F (ASTM D113).

h. Ring and ball softening point (ASTM D36).

i. Resiliency (ASTM D3583).

15. In addition to the binder tests noted above, which were conducted on virgin materials, several binder tests were conducted on all six test binders after aging in the Thin Film Oven and the Weatherometer. The Thin Film Oven uses the traditional heat-aging approach while the Weatherometer imparts cycles of heat, ultraviolet radiation, and moisture to the test samples. The tests conducted on the aged binders included:

a. Absolute viscosity at 140°F (ASTM D2171).

b. Penetration at 77°F (ASTM D5).

c. Ductility at 77°F (ASTM D113).

d. Ring and ball softening point (ASTM D36).

e. Percent weight loss.

16. Standard PFC mix designs were conducted using varying binder contents and mix temperatures. An analysis of the effects of these mix design variables on the resulting voids criteria was used to determine the proper mix design procedure for asphalt rubber PFC mixtures. Additional tests conducted on the varying types of PFC mixtures included:

a. Binder drain off tests.

b. Permeability tests.

c. Stripping (water sensitivity) tests.

(1) ASTM soak test (ASTM D1664).

(2) Texas boiling test.

(3) Porewater pressure debonding test.

17. Two or three repetitions of many of the tests were performed in order to provide sufficient data for a complete analysis. A total of 420 binder tests were conducted in Phases I and II of this study with approximately the same number of tests performed on PFC mixtures in Phase III. From the combined analyses of these tests, the potential benefits of using asphalt rubber binders in PFC's were determined. Recommendations on the suggested asphalt rubber binder types and mix design procedure to achieve optimum field performance were also established.

PART III: LITERATURE REVIEW

Field Applications

18. The earliest documented application of asphalt rubber binders was in 1964 when the City of Phoenix, AZ, used asphalt rubber based surface treatments in its street maintenance program. Charania, Cano, and Schnormeier (1991) reported on this application and Phoenix continued use of asphalt rubber pavement systems since that time. The earlier applications of asphalt rubber binders in Phoenix were limited to chip seals used as either pavement surface treatments or as stress absorbing membrane interlayers (SAMI). The use of asphalt rubber became much more prominent in Phoenix beginning in 1971 when the city began using these binders in various types of hot mix applications including PFC's. Since that time, Phoenix has paved almost 3,600 lane miles of asphalt rubber pavements using almost 3.6 million scrap tires.

19. Several US transportation agencies have reported recent field experiences with asphalt rubber binders. The State of Texas has perhaps the most experience with asphalt rubber field trials. Heine (1990) reported that since 1983, 3.6 million waste tires have been used in the 85,000 tons of asphalt rubber mixtures found on various types of pavement systems throughout Texas. These asphalt rubber pavement trials were reported to be located in 20 of the state's 24 highway districts. Most of these trials have indicated favorable results for asphalt rubber binders.

20. Van Kirk (1991) reviewed the California Department of Transportation's (Caltrans) numerous experiences with asphalt rubber pavements in a recent report. From 1978 to 1990, Caltrans used asphalt rubber binders in 21 pavement projects, including five PFC applications. The asphalt rubber binders were used in these projects to provide a more cost-effective and durable pavement. The California projects have identified a number of advantages in using asphalt rubber in PFC pavements, including reduced thickness with equal pavement performance, better resistance to freeze-thaw damage, better resistance to damage from snow plows and tire chains, and more

effective construction at lower ambient temperatures because of higher mix temperatures.

21. Scherling (1988) described two airfield pavement projects at Muskegon County Airport in Michigan, where asphalt rubber binders were used in PFC applications. The first project took place in 1983 when both of the airport's two main runways where overlaid with a 3/4-in. asphalt rubber PFC. After 3 years, the asphalt rubber PFC applications had performed well enough to be specified for use in another overlay project in 1987. The 1987 project used the same 3/4-in. asphalt rubber PFC design to overlay a secondary runway at Muskegon County Airport. Scherling's 1988 report concluded that all of the asphalt rubber PFC pavements were performing well.

22. In a report to the Washington State Department of Transportation, Anderson (1987) described a 1,200-ft section of asphalt rubber PFC on Interstate 5 in Vancouver, WA. The Interstate 5 test section is being evaluated to satisfy the local demand for a functional PFC with greater resistance to raveling. In his conclusions concerning the future of asphalt rubber PFC applications, Anderson stated that the most significant need was a means of determining the proper amount of binder in the final mix.

US State Agencies Research

23. A number of state transportation agencies have initiated asphalt rubber research programs in recent years. In a January 1991 report to the American Association of State Highway and Transportation Officials (AASHTO), Story (1991) mentions a survey response on the state agencies' experiences with the use of asphalt rubber binders. Four state agencies cited current research programs on asphalt rubber. Moore (1991) reported that as of February 1991, 15 states had enacted legislation which encouraged the use of asphalt rubber pavement binders. The recent growth of asphalt rubber technology coupled with the environmental concerns of waste tire disposal have created this political interest.

24. The Florida State legislature passed Senate Bill 1192 in 1988 which directed the Florida Department of Transportation (DOT) to expand its use of ground tire rubber in state-owned pavements (Roberts et al 1989). Florida DOT engineers have targeted PFC's as their pavement system best suited for asphalt

rubber applications. In a report to the Florida DOT in 1989, Ruth (1989) concluded that asphalt rubber binders would allow for higher binder contents in open-graded mixes, thus providing improved durability and retention of aggregates.

25. One of the most recent states to get involved in asphalt rubber research is Mississippi. State laws were passed in the Mississippi legislature on July 1, 1991 requiring the Highway Department and the State Department of Wildlife, Fisheries, and Parks to develop some uses for waste tires (Stallworth 1991). In light of this legislation, the Mississippi State Highway Department has investigated the potential uses of asphalt rubber in state owned pavements, and is expected to construct its first asphalt rubber field trial during the fall of 1991.

US Federal Government Research

26. Shuler et al (1986) reported on an extensive research study on asphalt rubber performed for the Federal Highway Administration (FHWA) during the mid-1980's. This study was prompted by past research studies which proved that the addition of ground tire rubber to asphalt cement imparted additional elasticity to the binder. Also, the FHWA was responding to the United States' growing environmental concerns over the 280 million waste tires it generates annually. The FHWA study concluded that asphalt rubber binders can dramatically improve the structural properties of asphalt concrete mixtures.

27. In a study conducted for the Federal Aviation Administration (FAA), Roberts and Lytton (1987) developed an interim mix design procedure for asphalt rubber concrete. Although the mix design method and other laboratory methods developed by this study were recommended for future asphalt rubber pavement projects, the authors recommended that field trials should be conducted to prove the validity of these new test methods. Some of the more recent airfield projects used these new test methods, and the FAA continues to monitor these projects to determine if they were designed adequately.

International Research

28. In many European countries, the use of and research on PFC's are much more extensive than in the United States. At a recent international pavements conference, representatives of several European countries reported extensive uses of PFC's, but cited a need for a more durable binder (Elsenring, Koster, and Scazziga 1990; Perez-Jimenez and Gordillo 1990; Van Der Zwan et al 1990). Pavement engineers from Belgium reported that of the 2 million square meters of PFC placed in their country, 60 percent contains asphalt rubber binders (Van Heystraeten and Moraux 1990). French engineers reported similar favorable experiences with asphalt rubber binders in PFC's since their studies with these materials began in 1982 (Sainton 1990).

29. In addition to the European market, asphalt rubber has attracted the attention of Middle Eastern countries attempting to deal with pavement problems caused by hot climates. Fernando and Guirguis (1983) reported on their asphalt rubber research for the Ministry of Public Works in Kuwait. The Government of Kuwait was investigating modified binders to help combat premature failures of asphalt pavements caused by their country's harsh summer climate. In reference to this issue, the authors stated that reclaimed rubber was the cheapest organic polymer that could be added to asphalt cement to provide the required improvements. The study concluded that asphalt rubber binders were more viscous at high temperatures, and when used in pavements subjected to hot climates, the binders were more resistant to distortion and more durable.

PART IV: TESTING EQUIPMENT AND PROCEDURES

30. Numerous asphalt binder and mixture tests were conducted in the laboratory to determine the effectiveness of asphalt rubber binders in PFC's. Standard test methods and a number of specialized testing procedures were employed in this laboratory study. Each set of tests was designed to comparatively analyze the engineering properties critical to the field performance of a PFC. The test plan for this study was organized into three separate phases: Phase I included the binder tests, tests of aged binders were conducted in Phase II, and Phase III included all of the open-graded mixture tests. The laboratory equipment and test procedures used in each of the three phases are discussed in the following paragraphs. The results of all laboratory tests are presented and discussed in Parts IV, V, and VI.

Phase I, Binder Tests

Viscosity

31. Perhaps the most important physical property that can be determined for an asphalt binder is its viscosity, which is a measure of its resistance to flow when in the liquid state. Viscosity measurements, when determined across a range of temperatures, directly relate to an asphalt mixture's mixing, construction, and performance characteristics. The asphalt binder grading methods used throughout the world are all, at least in part, based on viscosity. Accurate determinations of asphalt rubber viscosity are more difficult to obtain in comparison with standard asphalt cements. This is true because asphalt rubber binders are actually two-phase systems containing small rubber particles suspended in the asphalt cement. The presence of these rubber particles has been known to affect the viscosity measurements of asphalt rubber binders when using standard test methods (Roberts et al 1989). The importance of having a reliable viscosity test method and the documented difficulties in measuring asphalt rubber viscosities lead to the selection of four viscosity test methods for this study. These test methods included three industry standards, the kinematic, absolute and Brookfield methods, and a new test method known as the Haake viscosity test.

32. The kinematic and absolute viscosity tests are specified by ASTM D2170 and ASTM D2171 (1991), respectively. Both test methods use capillary viscometer tubes submerged in temperature control baths, with the kinematic viscosity test conducted at 275°F and the absolute viscosity test conducted at 140°F (Figures 2 and 3). Kinematic viscosity relates to a binder's properties during asphalt mixture plant mixing and construction laydown. Absolute viscosity is relative to the binder's condition in the pavement during the peak high temperatures of the summer months. The Brookfield and Haake tests determine viscosity by measuring the binder's resistance to shearing forces imparted by a rotating spindle which is inserted in the liquefied binder. Both test methods can be conducted over any range of temperatures above the binder's solid to liquid transition range. The Brookfield viscosity test is described by ASTM D2994 (1991) and makes use of a stationary testing apparatus (Figure 4). The Haake viscosity test involves the same principles as the Brookfield test, but it makes use of a recently designed, compact, portable, hand-held device (Figure 5). Of all four viscosity test methods evaluated by

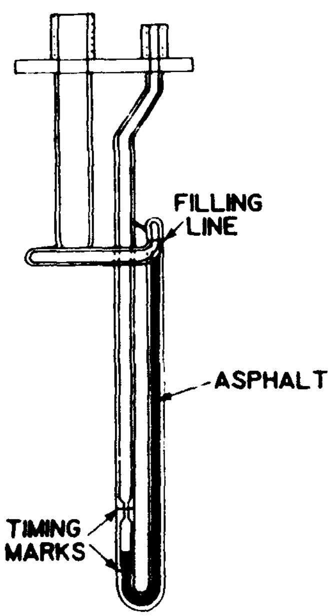

Figure 2. Viscometer tube used to conduct kinematic viscosity test (after Roberts et al 1991)

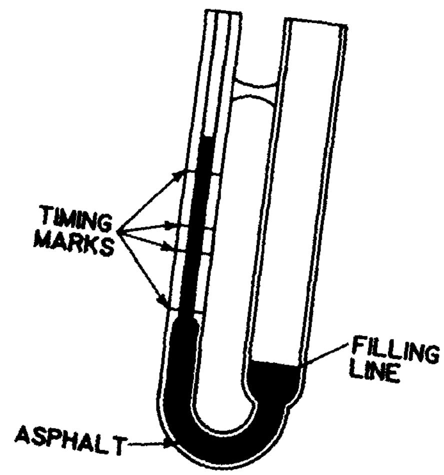

Figure 3. Viscometer tube used to conduct absolute viscosity test (after Roberts et al 1991)

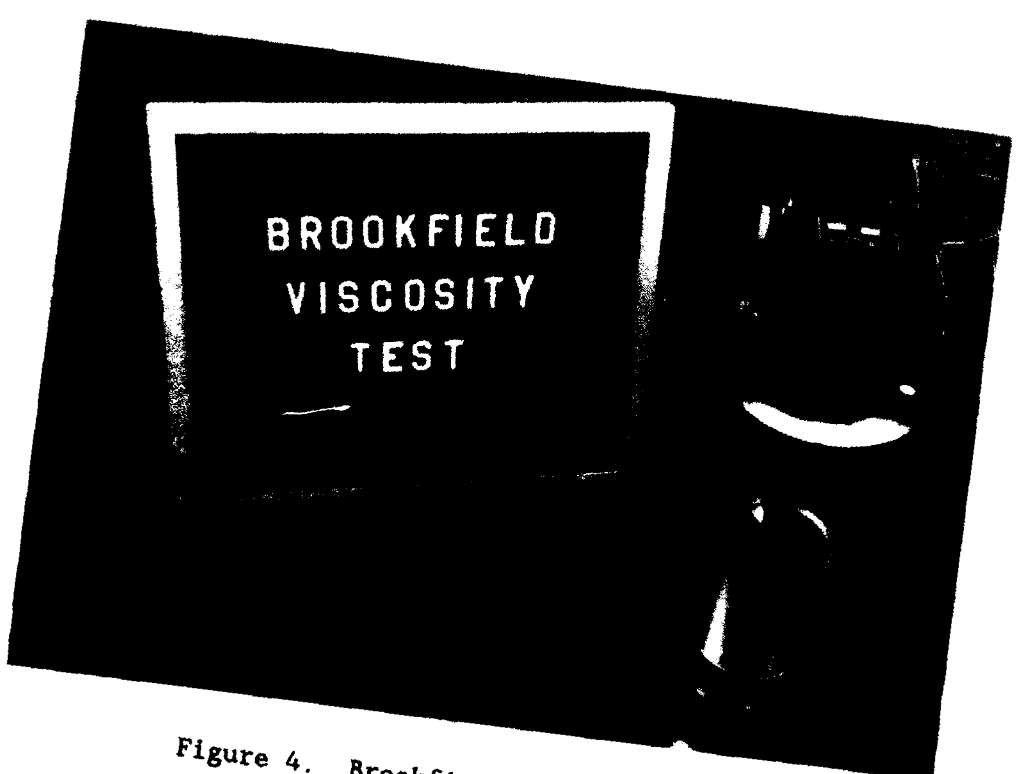

Figure 4. Brookfield viscosity test

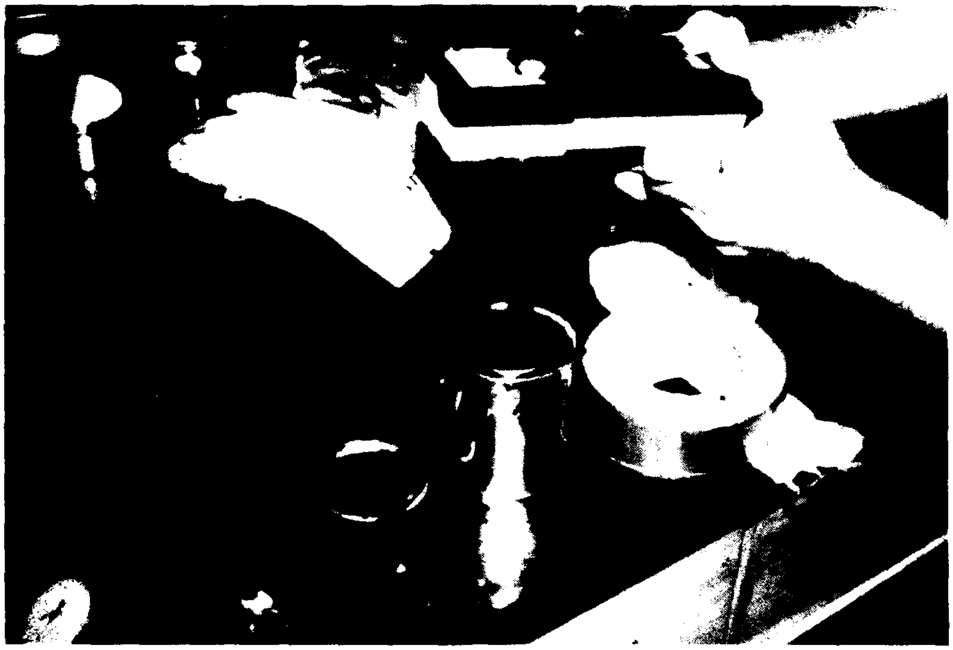

Figure 5. Haake viscosity test

this study, the Haake method proved to be the quickest and most convenient to conduct.

Penetration

33. Two types of penetration tests were conducted on the six test binders in order to evaluate their relative consistency and the effects of reduced temperature on this measurement. The standard needle penetration test (Figure 6), which is conducted in accordance with ASTM D5 (1991), was conducted at two temperatures, 39°F and 77°F. The test involves measuring the penetration depth of a standard needle which is forced into an asphalt binder sample under a 100 g load for 5 sec. Figure 7 is a schematic of how an asphalt sample's penetration value is measured.

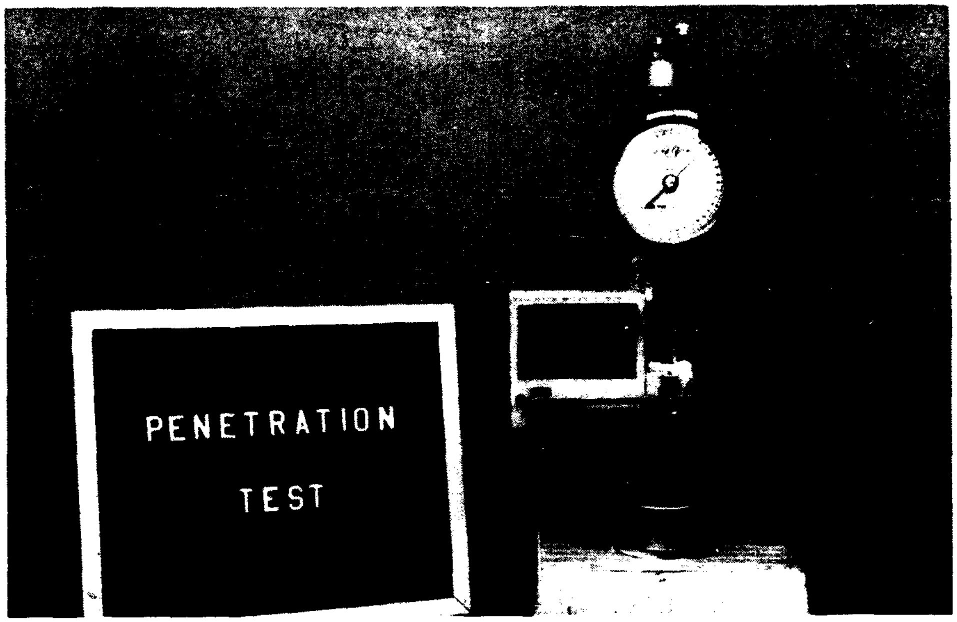

Figure 6. Needle penetration test

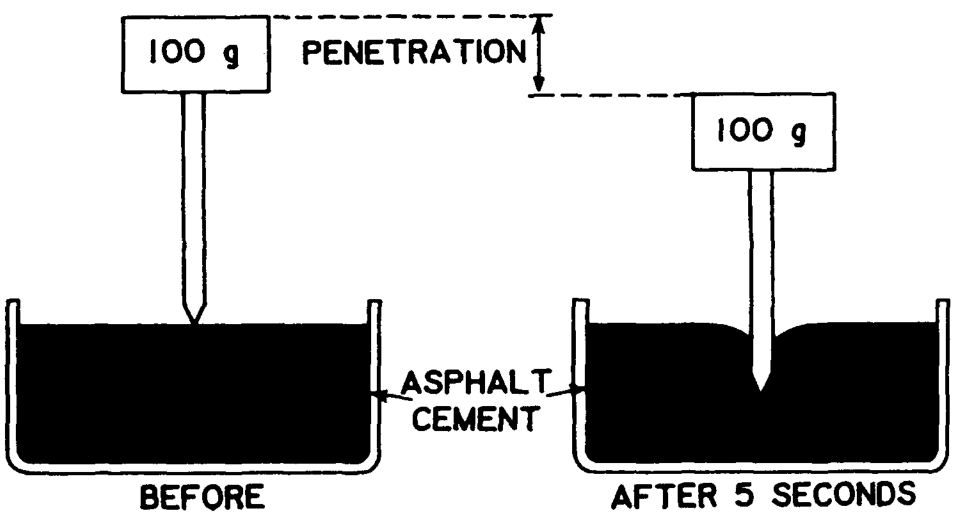

Figure 7. Schematic of needle penetration measurement (after Roberts et al 1991)

34. Since asphalt rubber binders contain suspended particles of rubber, it is entirely possible for a standard penetration needle to inconsistently come into contact with these particles during the test. Therefore, another type of consistency test was needed which would theoretically eliminate this potential problem. The cone penetration test (ASTM D217) (1991) was selected for this purpose since the test method makes use of the same basic equipment and loading scheme, with the exception of the penetrating tool being different. A cone-shaped tool is substituted for the needle (Figure 8), and the metal cone is forced into the asphalt binder sample under the same loading conditions and temperatures as for the needle penetration test. Since the cone is displacing a larger area of the sample during the test, it would eliminate any potential negative effects on testing reliability caused by the suspended rubber particles.

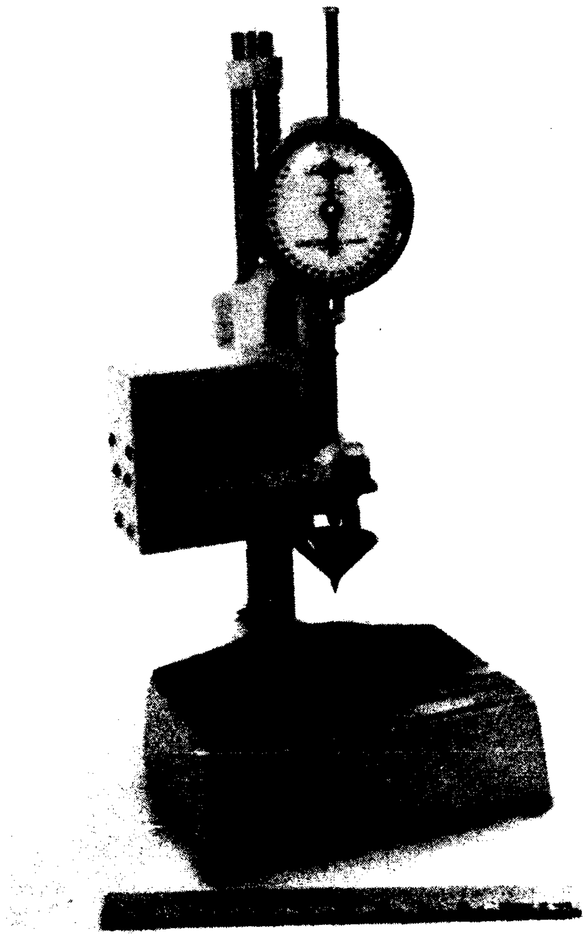

Figure 8. Cone penetration test

Ductility

35. A series of ductility tests (ASTM D113) (1991) were run on all six test binders at two temperatures, 39°F and 77°F. The ductility test measures the distance that a standard size asphalt binder briquette specimen will elongate before breaking when the specimen ends are pulled apart at a specified speed. The test samples are maintained at a specified temperature in the water bath where the sample remains during testing. In measuring the binder's elastic properties, the ductility test has been associated with a number of physical properties such as shear resistance, temperature susceptibility and low-temperature pavement performance. Regardless of the physical property associated with ductility, higher ductility values are desired to help improve pavement performance. The ductility test is shown in Figure 9.

Softening point

36. The ring and ball softening point test was used in this study to determine the temperature at which the test binders began the phase change between solid to liquid state. This temperature becomes important in warm climates when pavement temperatures approach the binder softening point

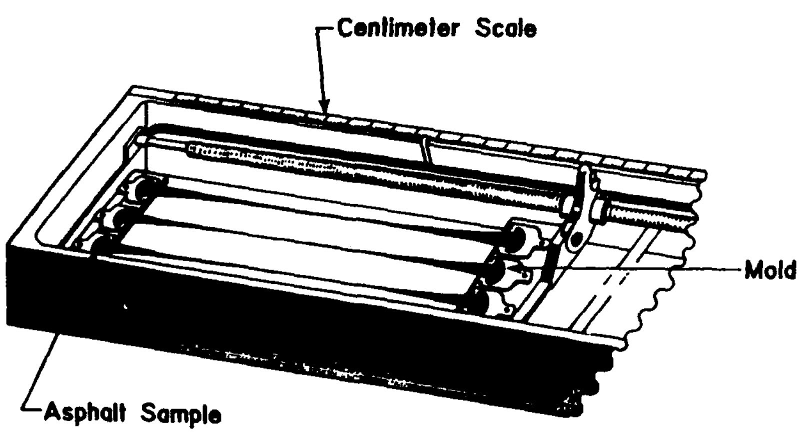

Figure 9. Ductility test (after Roberts et al 1991)

temperature, and the pavement becomes tender and unstable under traffic. Under these conditions, a higher softening point temperature for the binder is desirable. The ring and ball method (ASTM D36) (1991) measures this value by taking a brass ring filled with asphalt binder and suspending it in a beaker filled with water. A steel ball of specified dimensions and weight is placed in the center of the sample, then the water bath is heated at a controlled rate. When the asphalt binder softens, the ball and asphalt binder sink toward the bottom of the beaker. The softening point temperature is recorded at the instant the softened asphalt binder sinks the prescribed distance and touches the bottom plate. The ring and ball softening point test apparatus is shown in Figure 10.

Resiliency

37. The resiliency test (ASTM D3583) (1991) was included in this study to determine if the addition of ground crumb rubber to an asphalt binder would significantly affect the resulting binder's elastic resilience properties. To determine this elastic resilience property, the binder sample is first hot-poured into a container similar to that used for the penetration test.

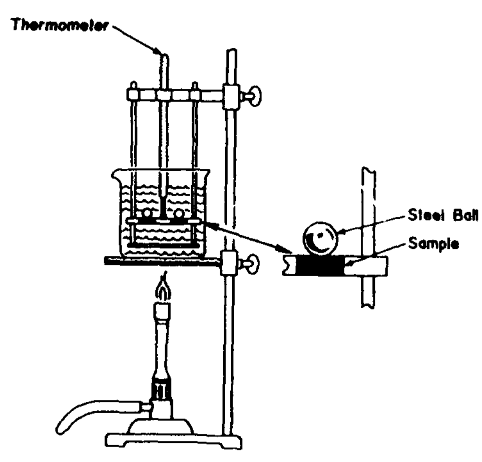

Figure 10. Ring and ball softening point test
(after Roberts et al 1991)

The specimen is air-cured for 24 hr prior to testing. The specimen is then conditioned in a 77°F water bath for 1 hr where it will remain throughout the testing. A ball penetration tool is substituted for the needle on a standard penetrometer (Figure 11) and forced into the asphalt specimen until a specified penetration depth is reached. The load on the penetration ball is held for 20 sec, then released, with only the dead weight of the penetration ball and loading arm resting on the sample. The resulting elastic deformation recovery is recorded 2 min after the load is released and the percentage of the original penetration depth is calculated. The recovery percentage gives an indication of the binder's elastic resilience properties with higher recovery values indicating more resistance to elastic strain.

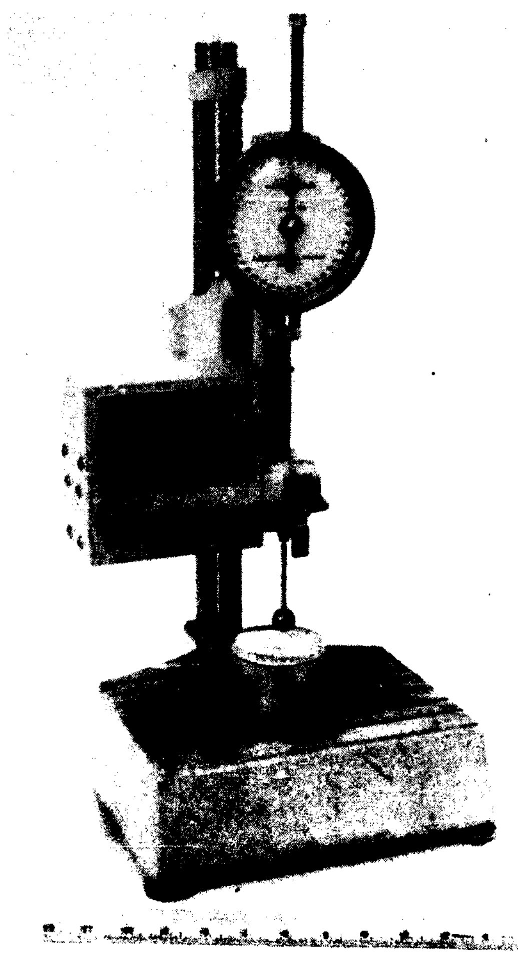

Figure 11. Resiliency test

Phase II, Accelerated Aging Tests

38. A series of binder tests were conducted in Phase II of this study on specimens which were conditioned in the laboratory by two types of accelerated aging test methods. The thin film oven test was used to determine the effects of short-term binder hardening which occurs when asphalt binders are mixed at high temperatures with hot aggregates at the asphalt plant. The effects of long-term age hardening, which occurs throughout the life of the pavement and results from continued exposure to the environment, were determined by aging the test binders in the weatherometer. The binder tests conducted on the laboratory-aged specimens included the 140°F absolute viscosity, 77°F penetration, 77°F ductility, and softening point tests. A weight loss percentage due to aging was also measured.

Thin film oven

39. The thin film oven test (ASTM D1754) (1991) is conducted by placing a 50 g sample of asphalt binder in a specified cylindrical flat-bottom pan, resulting in a specimen thickness of about 1/8 in. The pan containing the binder specimen is placed on a rotating shelf in a 325°F oven. The oven shelf rotates at five to six revolutions per minute and the sample is kept in the oven for 5 hr. At this time, the specimen is removed from the oven and transferred to the specified container or mold necessary for further testing. The thin film oven test is shown in Figure 12.

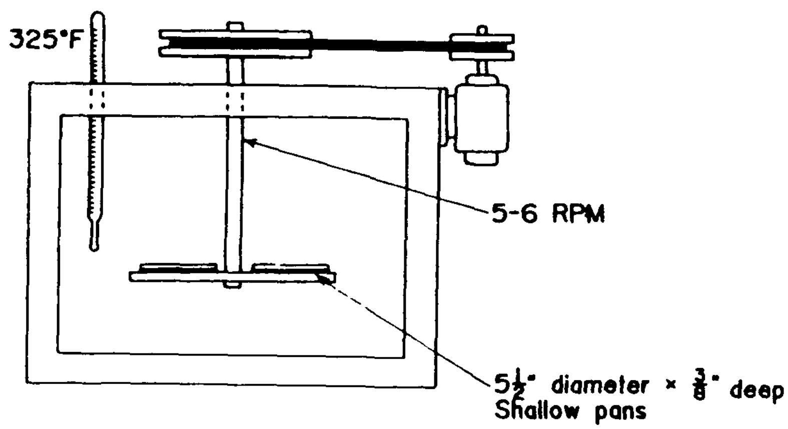

Figure 12. Thin film oven test (after Roberts et al 1991)

Weatherometer

40. The weatherometer simulates environmental aging by using ultraviolet (UV) radiation, moisture, and heat. These three elements are imposed on the specimens in automatically controlled cycles while in an environmentally controlled test chamber. The UV radiation is imparted by dual carbon arc lamps positioned in the center of the environmental chamber. Moisture effects are controlled by fine mist spray nozzles and humidity sensors. Thermostatically controlled heating elements within the test chamber control the test temperature. The test samples were placed in the same containers as used for the thin film oven test, but for the weatherometer tests, the containers were filled flush to the top to prevent water from collecting on top of the specimens. Up to eight specimens were placed on a wire mesh shelf located in the center area of the chamber and the shelf rotated at one revolution per minute during testing. The procedure used for aging the binder specimens in the weatherometer followed that prescribed by Federal Specification SS-S-00200E which specifies standard tests for two-component, fuel-resistant pavement joint sealing materials. This standard describes the use of the weatherometer for accelerated aging of laboratory samples. Short-term aging is described as one day of weatherometer aging using 20 cycles of the following chamber conditions:

51 min UV light, then
9 min UV light with water spray
60 min total cycle time
140°F chamber temperature during entire conditioning period

This 20 cycle test is conducted in 1 day's time. Long-term aging is simulated by repeating this same test for 8 days under the same conditions. Both the 1- and 8-day tests were conducted in this study. Figure 13 shows the weatherometer with a number of binder specimens in place for testing. A close-up view of a group of test binders immediately after aging in the weatherometer is shown in Figure 14.

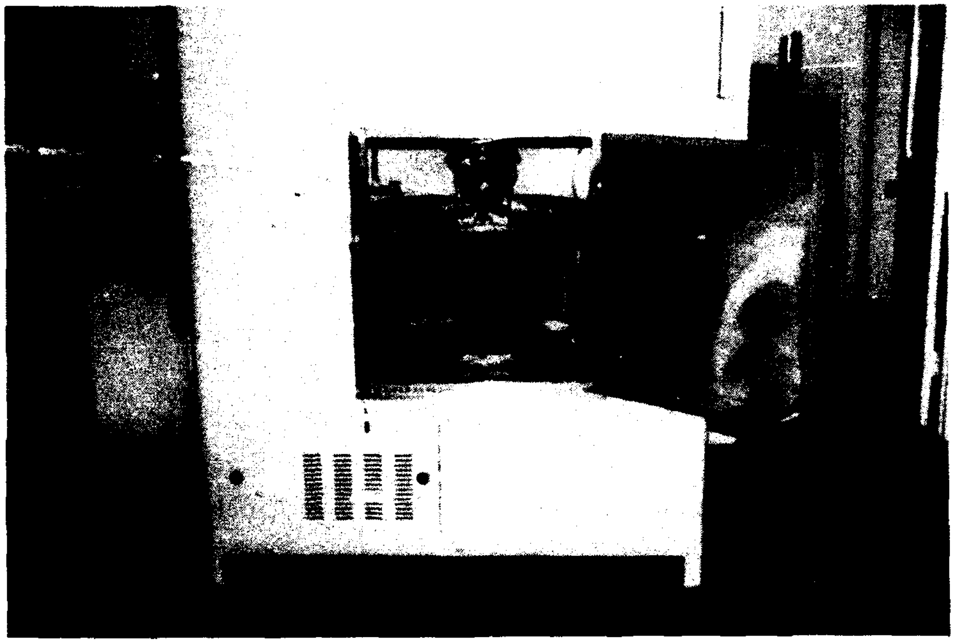

Figure 13. Weatherometer used for accelerated aging tests

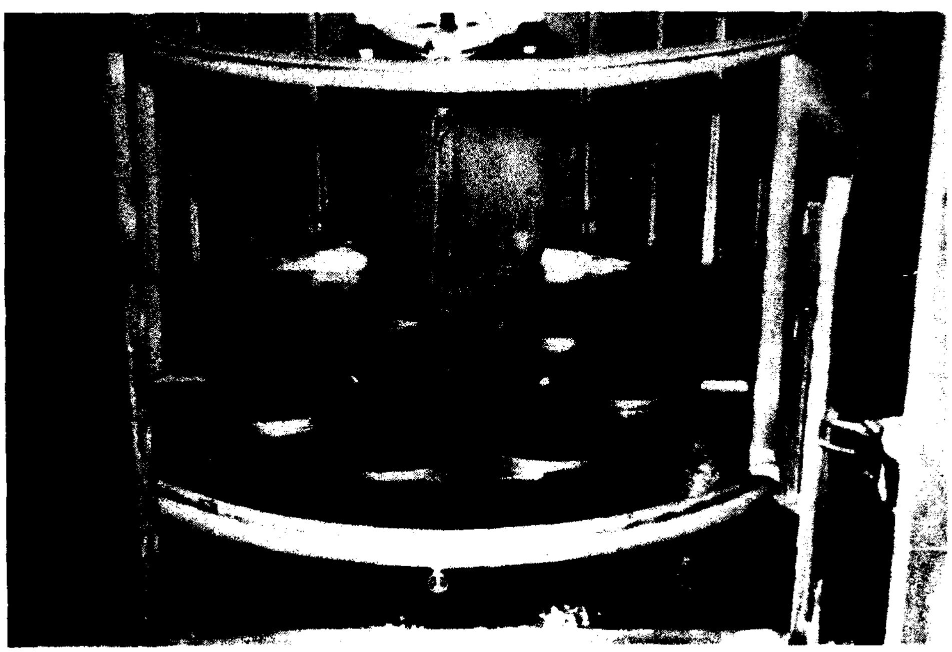

Figure 14. Aged binder samples in weatherometer

Phase III, Open-Graded Mixture Tests

41. A number of open-graded mixture tests were conducted during Phase III of this study. A single aggregate source and gradation were used in all Phase III tests in order to isolate the binder effects. Laboratory tests for evaluating open-graded asphalt mixtures are not very common, and a great deal of research into the literature was necessary to find a group of tests suitable for this phase of the study.

Mix designs

42. The most common approach in designing open-graded asphalt mixtures is to estimate the optimum binder content by conducting the Centrifuge Kerosene Equivalency (CKE) test on the proposed job aggregate. The Federal Highway Administration (1974) and the US Army Corps of Engineers (Headquarters, Department of the Army 1984) both recommend this design procedure in their respective current PFC mix design guidance. The CKE test is described by California Test Method No. 303-F and is a measure of the test aggregate's surface area and absorption characteristics. The test method for open-graded mixtures involves a measure of the percent of SAE No. 10 oil retained on a 100-g sample of aggregates after a 5-min soak period and a 17-min free-draining period in a specified funnel. The difference between the aggregate sample's weight before and after the free-draining period is recorded as the percent oil retained value. This value is used with a chart and accompanying equation (as described in Part VII of this report) to calculate an optimum binder content. The binder content derived from this test along with an aggregate source and gradation with a suitable performance history are historically the only two open-graded mixture design criteria used. Since an open-graded mixture containing 20 to 30 percent air voids lacks structural capacity, it is virtually impossible to measure any meaningful strength properties in the laboratory. This prevents the evaluation of load applications and stress levels during the mix design tests.

43. Some open-graded mixture researchers have claimed that binder contents much higher than the CKE derived values are allowable with asphalt rubber binders (Page 1989, Ruth 1989, Shuler 1988). To validate this claim and to determine the limits of higher binder contents, a series of mix designs was conducted for each test binder. These 6-in. diam by 2-in.-thick specimens

were compacted with the Marshall hand hammer compactor using 25 blows on one side of the specimen. This compactive effort has been found to correlate with field densities of normally constructed open-graded mixtures (Ahlrich and Anderton 1991, White 1975). The resulting open-graded mixture specimens were weighed in air and in water to determine physical properties such as void content and density. Changes in these physical properties in relation to the binder type and binder content were used to determine the proper mix design method for open-graded mixtures containing asphalt rubber.

Binder drain off

44. When open-graded asphalt mixtures are produced at the plant, excess mix temperatures or binder contents can cause the binder to drain off of the mixture while in the haul trucks. This causes serious problems at the job site since some of the mixture will be undercoated with binder while other areas will be oversaturated with binder, depending on whether the mixture came from the top or bottom of the haul truck. These potential problems can be difficult to control when using normal asphalt cements since the optimum mixing temperature and binder contents are usually not far below the levels which cause excess binder drainage problems. To address this problem, laboratory binder drain off tests were conducted under various conditions of temperature and binder content.

45. The binder drain off test was devised during past research studies at WES (White 1975). The test method begins by preparing a 300-g sample of the open-graded mixture for each binder content. The samples are mixed and tested at the same selected temperature. Once the binder and aggregates are mixed thoroughly, each sample is spread evenly over the center area (approximately 6 in. in diameter) of a 1-ft sq glass plate (Figure 15). Each sample plate is labeled and placed in an oven preheated to the appropriate test temperature. The samples are removed from the oven after 2 hr and allowed to cool to room temperature. Once cooled, the amount of drainage to the bottom of the glass plate is observed to determine the percentage of the 6-in. diam center area covered with drained binder. This visually determined percent drainage value (in increments of 10 percent) is recorded as the test result. During the WES research study previously mentioned, White (1975) used field evaluations of 17 PFC pavements and an extensive laboratory study to determine that 50 percent drainage by this test is a reasonable upper

limit to prevent detrimental binder drainage during mixing and construction. The bottom of a binder drain off test sample is shown in Figure 16.

Figure 15. Preparation of binder drain off test sample

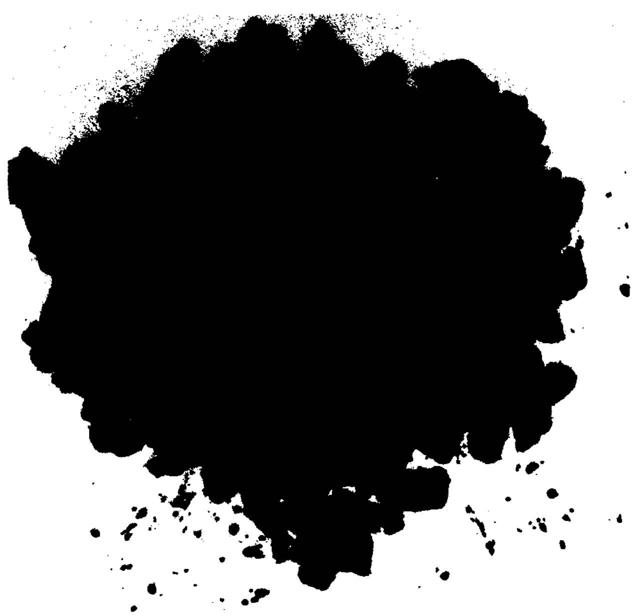

Figure 16. Bottom of binder drain off test sample after testing

Permeability

46. A laboratory permeability test, which was devised during previous research at WES on PFC's (White 1975), was conducted on open-graded mixture samples containing the various test binders. The test involves a time measurement of the flow rate for a known volume of water to pass through a representative sample of compacted, open-graded mixture. This falling head permeability test is shown in Figure 17. The test sample consists of 6-in.-diam specimens made of a 2-in.-thick compacted dense-graded asphalt layer topped with a 3/4-in.-thick PFC layer. The dense-graded mixture is compacted first and merely acts as a base for the PFC layer. The PFC layer is compacted on top of the dense-graded base using 10 blows of the Marshall hand hammer, resulting in a thickness and density representative of typical field conditions.

Figure 17. Falling head PFC permeability test

47. A 4-in.-diam clear plastic standpipe is used to hold a measurable head of water on top of the test samples. Before testing, a rubber O-ring is placed between the standpipe and the surface of the sample. A 100-lb surcharge load is applied to the standpipe to restrict surface drainage and to force most of the water to flow into the 3/4-in. PFC layer. Once the standpipe has been positioned and loaded, water is introduced by pump into the standpipe to a level above the 10 in. mark on the side of the standpipe. Addition of water is then stopped, and the time to fall from the 10- to the 5-in. level is measured with a stopwatch. This test is repeated three times and the average of the values is computed. The flow rate is determined from the relation $Q = VA$. Thus, for the 5-in. falling head of this test, the flow rate (Q) in milliliters per minute is equal to 15,436.8 divided by the time to fall in seconds. Higher flow rate values reflect a more effective PFC in wet weather conditions. A reasonable lower limit of flow rate for newly constructed PFC pavements is 1,000 ml/min.

Stripping

48. To complete the open-graded mixture laboratory analysis, three different stripping tests were conducted on each test binder. Stripping relates to the separation of binder and aggregate in the presence of water, and this phenomenon is one of the main causes of PFC pavement failure. The three tests used in this study were the ASTM D1664 "Standard Test Method for Coating and Stripping of Bitumen-Aggregate Mixtures" (ASTM 1991), the Texas Boiling Test, and the Porewater Pressure Debonding Test.

49. The ASTM D1664 stripping test is generally used to measure the compatibility between the binder and the aggregate in the presence of water, and is known to identify only those mixtures with extremely serious stripping potential. The test procedure begins with coating a representative 100-g sample of aggregates with the binder at the mix temperature appropriate for the given binder. After coating, the mixture is allowed to cool to room temperature. The coated aggregate is then transferred to a 600-ml glass container and immediately covered with approximately 400-ml of distilled water at room temperature. The coated aggregate remains immersed in the water for 16 to 18 hr. After this time, the water covered specimen is illuminated by a shaded lamp, and a visual determination of the aggregate surface area which

remains coated is made. The test result is recorded as either pass (above 95 percent binder retention) or fail (below 95 percent binder retention).

50. The Texas Boiling Test was conducted on each of the six test binders as an additional stripping test. The Texas Boiling Test measures stripping potential of an asphalt-aggregate mixture in a manner similar to the ASTM method, except that the sample is soaked in boiling water. The test method is described in detail by Kennedy, Roberts, and Kang (1984), but can be summarized as follows: A 300-g sample of representative aggregates is coated with the appropriate amount of binder at the appropriate mix temperature. The resulting mixture is transferred to a piece of aluminum foil and allowed to cool to room temperature for 2 hr. Once cooled, the mixture is added to a 1,000-ml beaker containing 500 ml of boiling distilled water. The water is maintained at a medium boil for 10 min, and the mixture is stirred with a glass rod during this time (Figure 18). During and after boiling, any stripping binder is removed from the water by skimming with a paper towel. After 10 min of boiling, the beaker is removed from the heat source and allowed to cool to room temperature. The water is then drained from the beaker and the wet mix is emptied onto a paper towel to dry. After drying for 1 day, the percentage of binder retained after boiling is visually determined, and this percent retention value is recorded as the test result. A typical test sample after boiling and drying is shown in Figure 19.

Figure 18. Texas boiling test

Figure 19. Typical sample after Texas boiling test

51. The final stripping test conducted on the open-graded test mixtures was the Porewater Pressure Debonding Test. This test was developed at the University of Arizona by Dr. Rudy A. Jiminez and is described in at least two literature references (Jiminez 1974, 1989). The laboratory equipment is used to simulate the cycles of porewater pressure imposed on PFC pavements by traffic tires when the PFC is saturated with water and certain conditions exist within the pore structure. At least a small percentage of PFC pore spaces are isolated enough from other pore spaces to develop pore pressures under the right conditions. The number of isolated pore spaces is known to increase when accumulations of tire rubber dust, silts, deicing materials, or other contaminants settle into the pore spaces of a PFC over time.

52. The Porewater Pressure Debonding Test method involves exposing the test samples to repeated cycles of porewater pressure and then measuring the tensile strength of these samples. These strength values are used with the strength values of control samples which do not undergo porewater pressure exposure to obtain a percent retained strength. Higher percent retained strength values indicate that a given binder and open-graded mixture is less sensitive than others to degradation damage resulting from traffic in wet conditions.

53. The Porewater Pressure Debonding Test equipment is shown in Figure 20. These 6-in. diam by 2-in.-thick specimens of open-graded mixtures

were first compacted to meet the optimum density and void conditions determined previously in the mix design tests. Three of the specimens are placed on a three-shelf carriage which is then placed into a stressing chamber. The chamber is filled with 122°F water, and the specimens are allowed to soak in this condition for 40 min. At this time, 20 in. of mercury vacuum is pulled on the stressing chamber and held for 5 min in order to completely saturate the specimens. After 5 min of vacuum pressure, the vacuum is released and more hot water is added to displace all air from the stressing chamber. Next, 1,000 cycles of water pressures varying from 5 to 30 psi are applied to the chamber, which takes approximately 10 min to complete. The water is then drained from the chamber and the specimens are removed. The specimens are cooled at ambient temperature for 10 min and then placed in a 77°F water bath for 1 hr. Finally, the sample is removed from the water bath and the "wet strength" of the sample is obtained using a built-in double punch tensile test. This same tensile strength test is used to obtain the "dry strength" of three control specimens which are conditioned by sealing them in plastic bags and placing them in the same 77°F water bath for 1 hr. The wet strength is divided by the dry strength, and the ratio is expressed as a percent retained strength.

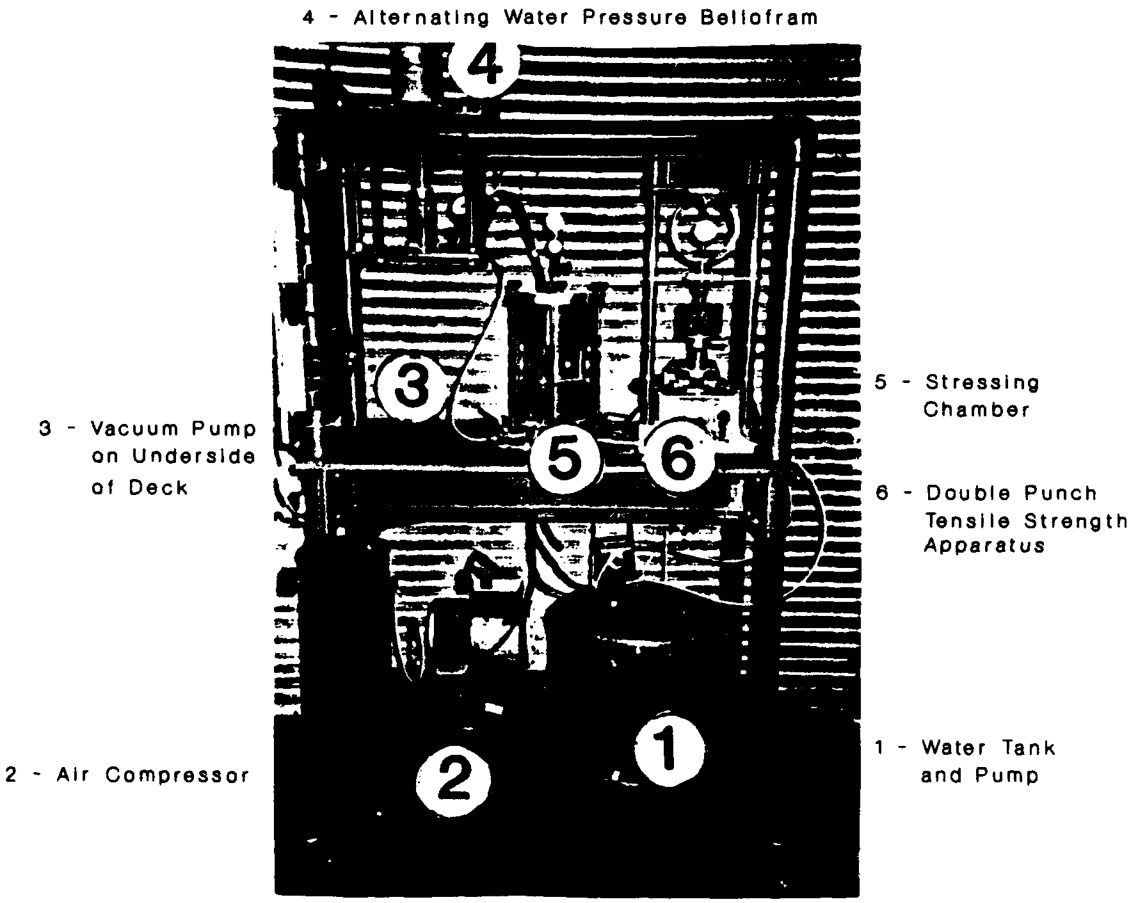

Figure 20. Porewater pressure debonding test equipment

PART V: PHASE I, PRESENTATION AND ANALYSIS OF DATA

54. The results of the Phase I laboratory tests are presented and discussed in this part of the report. The Phase I portion of this laboratory study was devoted to binder tests. The results of these binder tests were used to comparatively analyze the physical properties of each test binder, and to relate these properties to PFC field performance characteristics.

55. The six test binders evaluated by the Phase I tests and during the remainder of the study included three unmodified asphalt cements and three asphalt rubber blends. The three unmodified asphalt cements included an AC-5, AC-20, and AC-40 grade. The test results describing the standard physical properties of these three asphalt cements, as specified by ASTM D3381 (1991), are presented in Table 1.

Table 1

Asphalt Cement Properties

Test	AC-5	AC-20	AC-40
Absolute Viscosity (140°F, P)	654	2,390	4,575
Kinematic Viscosity (275°F, cSt)	141	400	358
Penetration (77°F, 100g, 5 sec, 0.1 mm)	114	44	27
Flash Point (Cleveland Open Cup, °F)	555	585	560
Solubility in Trichloroethylene (%)	99.8	99.9	100
Specific Gravity at 77°F	1.018	1.019	1.019
Tests on Thin Film Oven Residue			
Weight Loss (%)	0.45	0.14	0.16
Viscosity (140°F, max, P)	1,196	4,169	8,532
Viscosity (275°F, Cst)	182	350	446
Penetration (77°F)	74	29	20
Ductility (77°F, 5 cm/min, cm)	150+	150+	150+

56. The three asphalt rubber binders included the AC-5 asphalt blended with 16 percent (by weight) crumb rubber and 5 percent (by weight) extender oil. Extender oils are generally described as petroleum resins and are sometimes added to asphalt rubber binders to reduce viscosity. Another asphalt rubber blend included the same AC-5 asphalt blended with 17 percent crumb rubber. The third asphalt rubber binder was a blend of the AC-20 asphalt and 17 percent rubber. These three asphalt rubber blends were labeled as AC-5RE, AC-5R, and AC-20R for all tests in this study. The crumb rubber used in each asphalt rubber blend was made of 100 percent reclaimed waste tires milled to a consistent gradation as listed in Table 2. The reclaimed rubber appearance after milling and before adding to the asphalt cement is shown in Figure 21.

Table 2

Crumb Rubber Gradation

US Standard Sieve Size No.	Percent Passing
10	100
16	99.8
30	78.0
40	48.8
50	26.6
80	9.2
100	6.6
200	0.2

Figure 21. Crumb rubber after milling

57. The Phase I binder tests included four viscosity tests, two penetration tests, a ductility test, a softening point test, and a resiliency test. The results of all Phase I binder tests are listed in Table 3. The results of each individual binder test are analyzed separately in the remainder of this section.

Table 3

Phase I Binder Test Results

Test		AC-5	AC-20	AC-40	AC-5RE	AC-5R	AC-20R
Kin Vis, 275°F (cSt)		141	265	358	NT	NT	NT
Abs Vis, 140°F (P)		654	2,390	4,575	2,027	3,221	5,773
Brookfield Vis (P)	194°F	40	135	173	570	1,980	1,040
	221°F	18	20	30	215	243	233
	250°F	4	8	7	170	155	185
	275°F	3	4	6	83	88	93
Haake Vis (P)	194°F	10	40	80	350	150	350
	221°F	3	18	25	175	125	180
	250°F	2	6	9	125	112	137
	275°F	1	4	8	100	105	125
Penetration (0.1 mm)							
200g, 60 sec, 39°F		40	15	14	63	39	20
100g, 5 sec, 77°F		114	44	27	125	85	40
Cone Pen (0.1 mm)							
200g, 60 sec, 39°F		63	27	10	94	58	25
150g, 5 sec, 77°F		101	35	21	111	71	38
Ductility (cm)							
5 cm/min, 39°F		0	0	0	25.4	22.5	0.9
5 cm/min, 77°F		150+	150+	150+	18.7	20.2	35.0
Softening Pt. (°F)		112	129	134	133	143	151
Resiliency (% Rec.)		-40	-9	-4	-20	11	32

Note: NT = No Test

Kinematic Viscosity

58. Attempts were made to conduct the 275°F kinematic viscosity test on all six test binders. The tests on the asphalt rubber binders were unsuccessful. As expected, their high viscosity prevented proper flow through the required viscometer tube which significantly distorted the results. The kinematic viscosity tests conducted on the three asphalt cements produced test results in the normal range for each respective binder.

Absolute Viscosity

59. The 140°F absolute viscosity test was conducted using the standard viscometer tube specified by ASTM D2171 for the three asphalt cement test binders. A larger Asphalt Institute No. 400-600 tube, which is allowed by the ASTM D2171 standard, was used to conduct the asphalt rubber tests. The test results of all six test binders are graphically displayed in Figure 22. The viscosity values of the asphalt cements are all within normal ranges. It is significant to note the absolute viscosity increases caused by the addition of crumb rubber. In Figure 22, it is apparent that the AC-5RE binder is in the same viscosity range as the AC-20 binder. Also, the AC-5R binder viscosity falls somewhere between the AC-20 and AC-40 values, possibly representing an AC-30 asphalt cement viscosity range. The AC-20R tested well above the AC-40 in absolute viscosity. These relationships indicate that, in terms of the binder's visco-elastic nature at 140°F, an AC-5RE binder acts like an AC-20 binder, an AC-5R binder acts like an AC-30 binder, and an AC-20R binder acts like a viscous AC-40 binder. These comparisons could indicate significant benefits for pavements in variable climates if the lower grade asphalt cements of the asphalt rubber binders retain some of their desirable low-temperature properties.

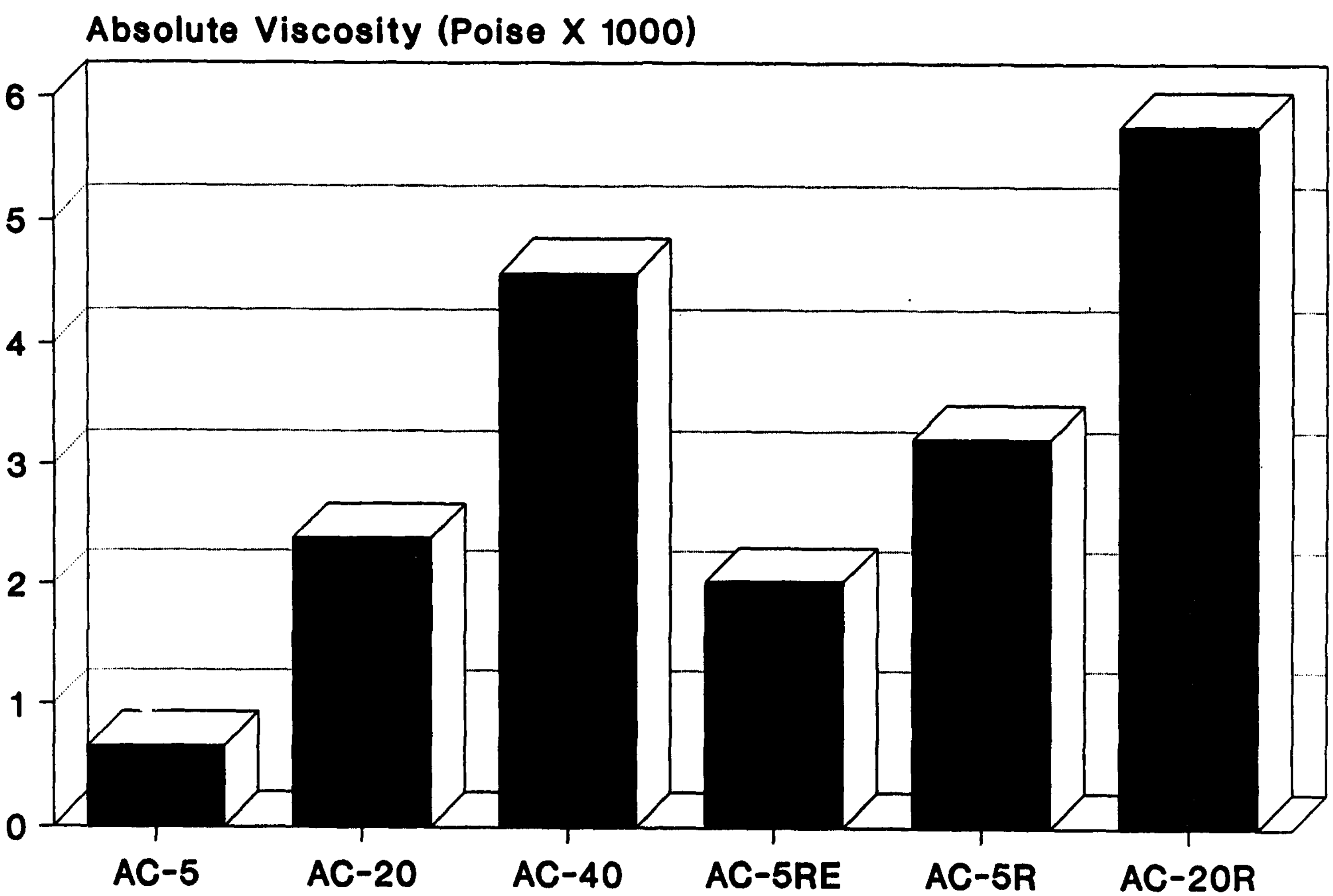

Figure 22. Absolute viscosity test results

Brookfield Viscosity

60. The results of the Brookfield viscosity tests are displayed in Figure 23. The test temperatures of 194°F, 221°F, and 250°F are recommended by the Brookfield viscosity test's ASTM standard. The 275°F test was added to identify binder viscosity properties closer to normal asphalt plant mix temperatures. The most obvious distinction of this graph is that the three asphalt rubber curves are grouped together in a viscosity range significantly higher than the three asphalt cement binders. The asphalt rubber curves generally fall in a viscosity range 10 to 20 times greater than the asphalt cements with the greatest variance between the two data groups occurring in the 250°F to 275°F temperature range. These significant differences in viscosity indicate that for the temperature range investigated, asphalt rubber binders will act very different from unmodified asphalt cements. Assuming that the asphalt rubber viscosities will continue to decrease with increasing temperature, then higher than normal binder and binder/aggregate mixture temperatures will be required during the mixing and construction of asphalt rubber PFC pavements.

Haake Viscosity

61. The results of the Haake viscosity tests are shown in Figure 24. The same test temperatures were used for the Haake tests as for the Brookfield tests so that a direct comparison between these two test methods could be made. As seen in Figure 24, the curves of the asphalt rubber binders grouped together at a viscosity range significantly higher than the asphalt cements. Therefore, the same inferences concerning binder and mix temperatures identified by the Brookfield viscosity tests are supported by the Haake tests.

62. The graphical representation of the Haake viscosity data also shows that the asphalt rubber curves have much less slope across the temperature range investigated, indicating less temperature susceptibility across this range. In many ways, a heat-stable binder in this temperature range is beneficial during mixing and construction. Also significant is the tight grouping of the asphalt rubber curves in the 220°F to 275°F range. This same phenomena is evidenced by the Brookfield viscosity curves in Figure 23.

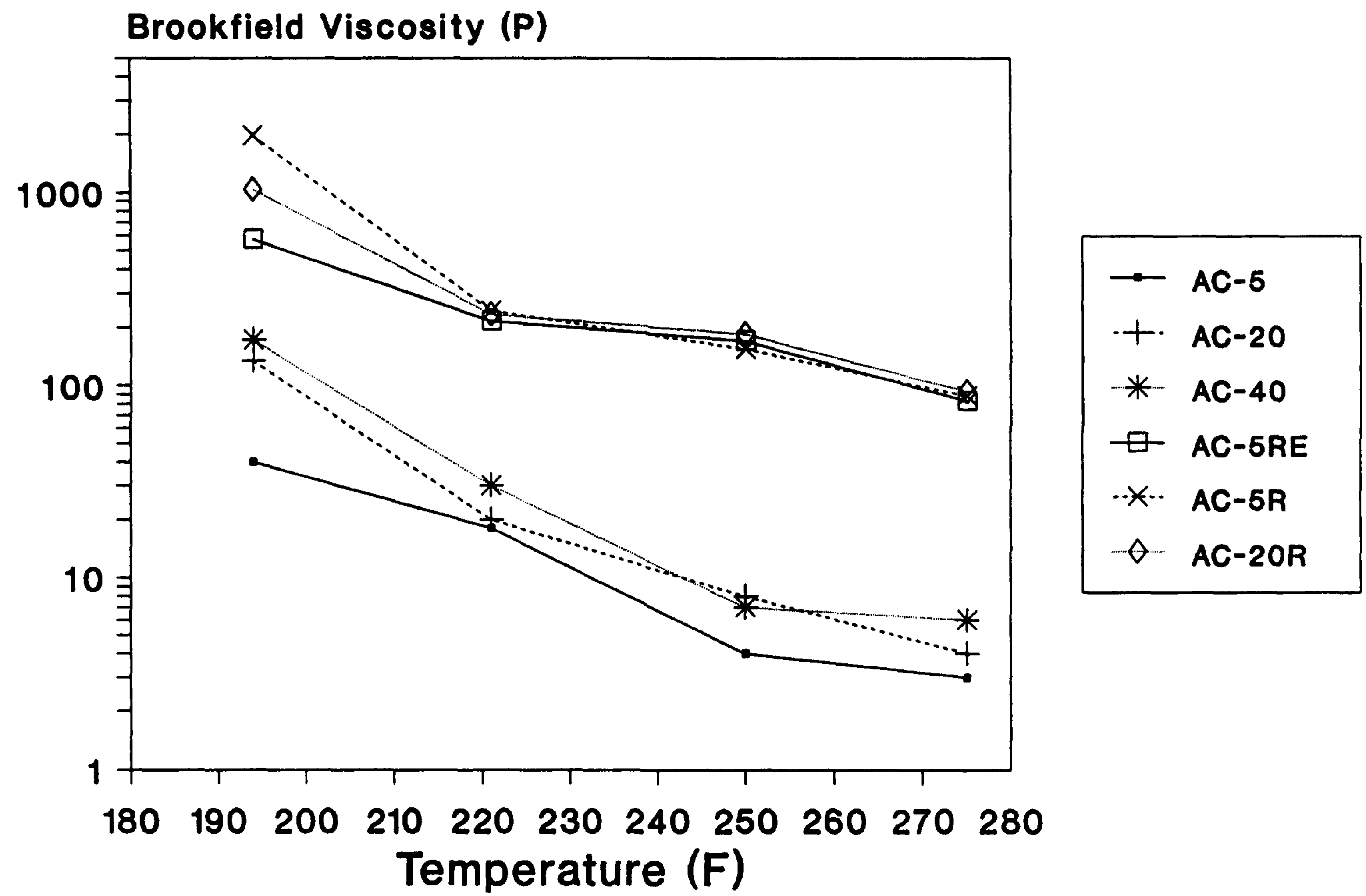

Figure 23. Brookfield viscosity test results

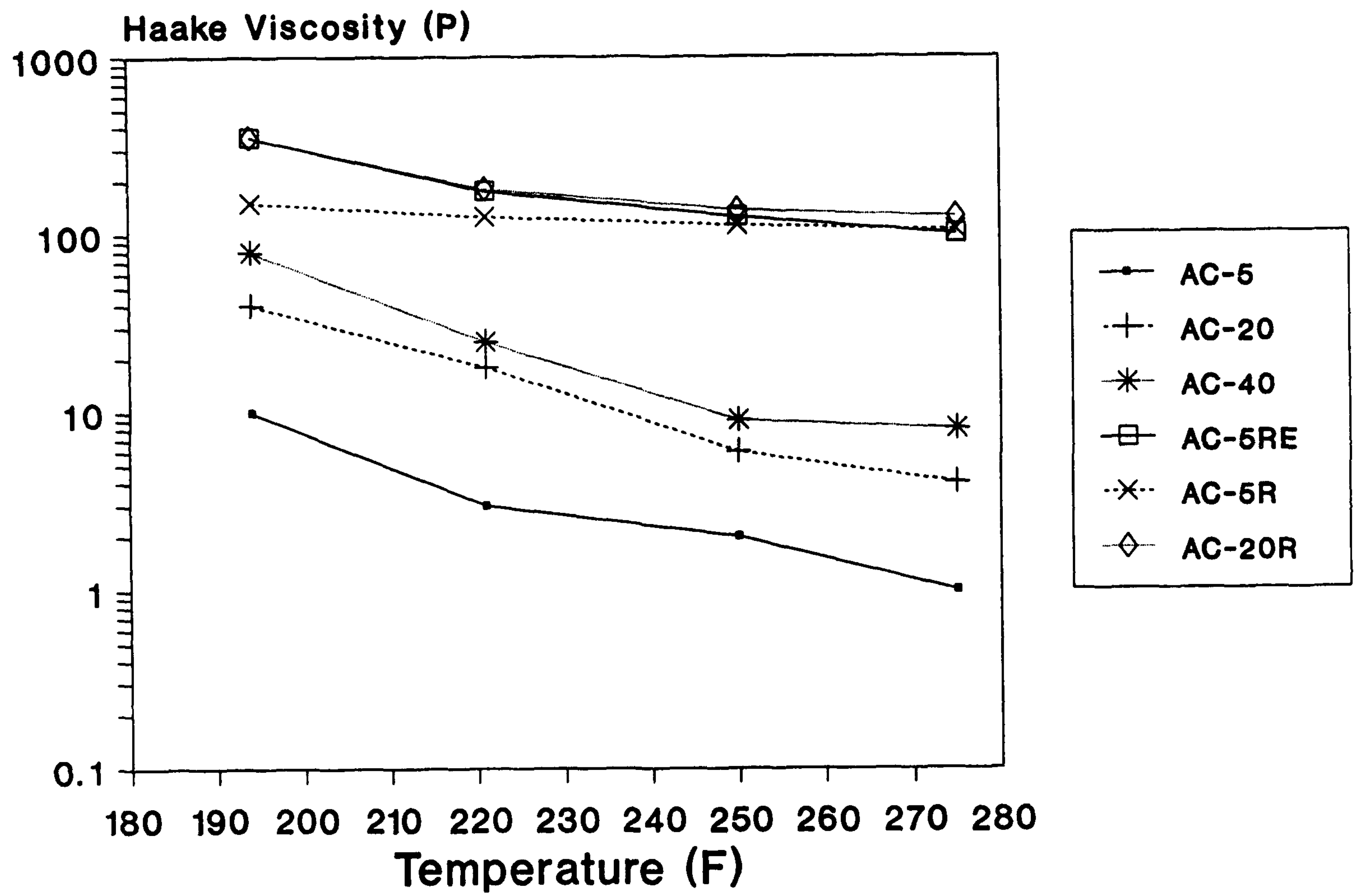

Figure 24. Haake viscosity test results

This would indicate that asphalt rubber PFC mixtures would act very similar in this temperature range, regardless of the viscosity of the base asphalt. This is not the case when using standard asphalt cements, and this fact is supported by the variances between the asphalt cement curves in Figures 23 and 24.

Penetration

63. The results of the needle penetration tests are displayed in Figure 25. The reduced penetration values with increasing binder viscosities seen in both the asphalt cements and asphalt rubber binders are considered normal. The effects of adding crumb rubber to an asphalt cement are determined in this case by comparing the AC-5RE and AC-5R data to the AC-5 data, and comparing the AC-20R data to the AC-20 data. In this analysis, the AC-5RE and AC-20R binders seem to offer low-temperature pavement benefits by increasing the 39°F penetration (which relates to reduced viscosity) while keeping the 77°F penetration values virtually unchanged. The AC-5R penetration data show a reduced penetration at 77°F while the 39°F penetration is virtually unchanged by the addition of crumb rubber.

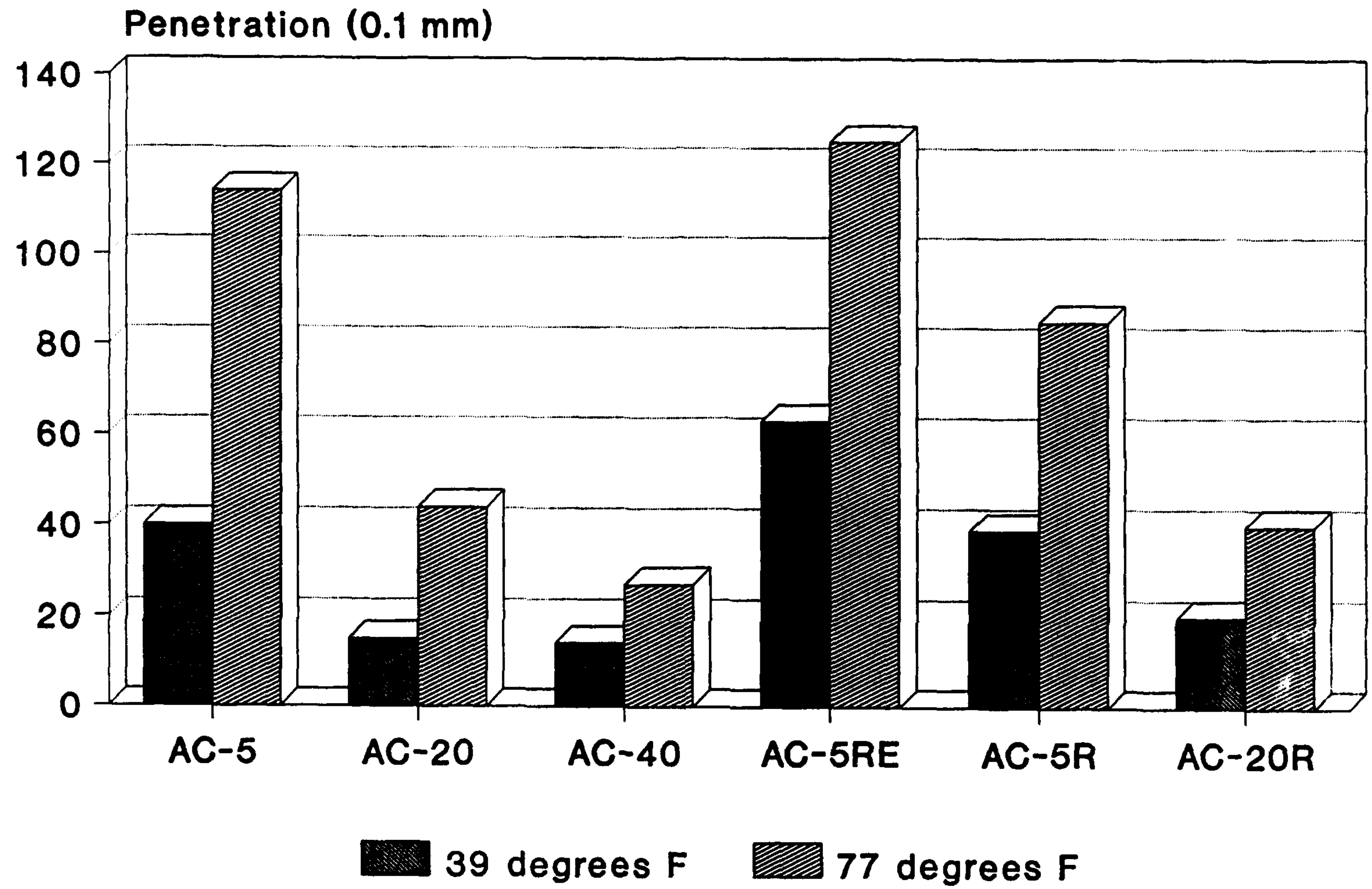

Figure 25. Penetration test results

Cone Penetration

64. The cone penetration test results are shown in Figure 26. As mentioned earlier in Part III, one of the main reasons for conducting the cone penetration test was to determine if the needle penetration data would be detrimentally affected by the suspended rubber particles in the asphalt rubber binders. The nearly identical data trends found in both the needle penetration and cone penetration data would indicate that the needle penetration test was unaffected by the rubber particles. The main difference between the two penetration tests was that the cone penetration test generally resulted in higher 39°F penetration values and lower 77°F penetration values. Even though this significantly closed the gap between the 39°F and 77°F data, the comparative trends between the rubber-modified and unmodified binders remained the same as identified in the needle penetration tests. The cone penetration tests not only validated these trends as discussed in the previous paragraph, but they also validated the use of the needle penetration test for asphalt rubber binders.

Ductility

65. The ductility test proved to be unsuitable for testing asphalt rubber binders as was the kinematic viscosity. Most asphalt binders of viscosity grade AC-20 and lower will surpass the limits of the standard ductility testing apparatus by stretching up to the 150 cm limit without breaking. Most AC-30 and AC-40 asphalt cements have ductility values above 100 cm. In the case of this study, the AC-5, AC-20, and AC-40 asphalt cements all resulted in test values of 150+ cm. In this study, the asphalt rubber samples usually failed at between 20 and 35 cm before the binder material could stretch out into the typical thin thread in the center of the test sample. These ductility test results for the asphalt rubber binders should not be considered as reliable indicators of the materials' elastic properties. This conclusion is supported by similar findings in an asphalt rubber study conducted by the Louisiana Department of Highways (Carey 1974). ASTM D113, which specifies the standard test method for the ductility test, also supports this conclusion in its definition of an acceptable ductility test:

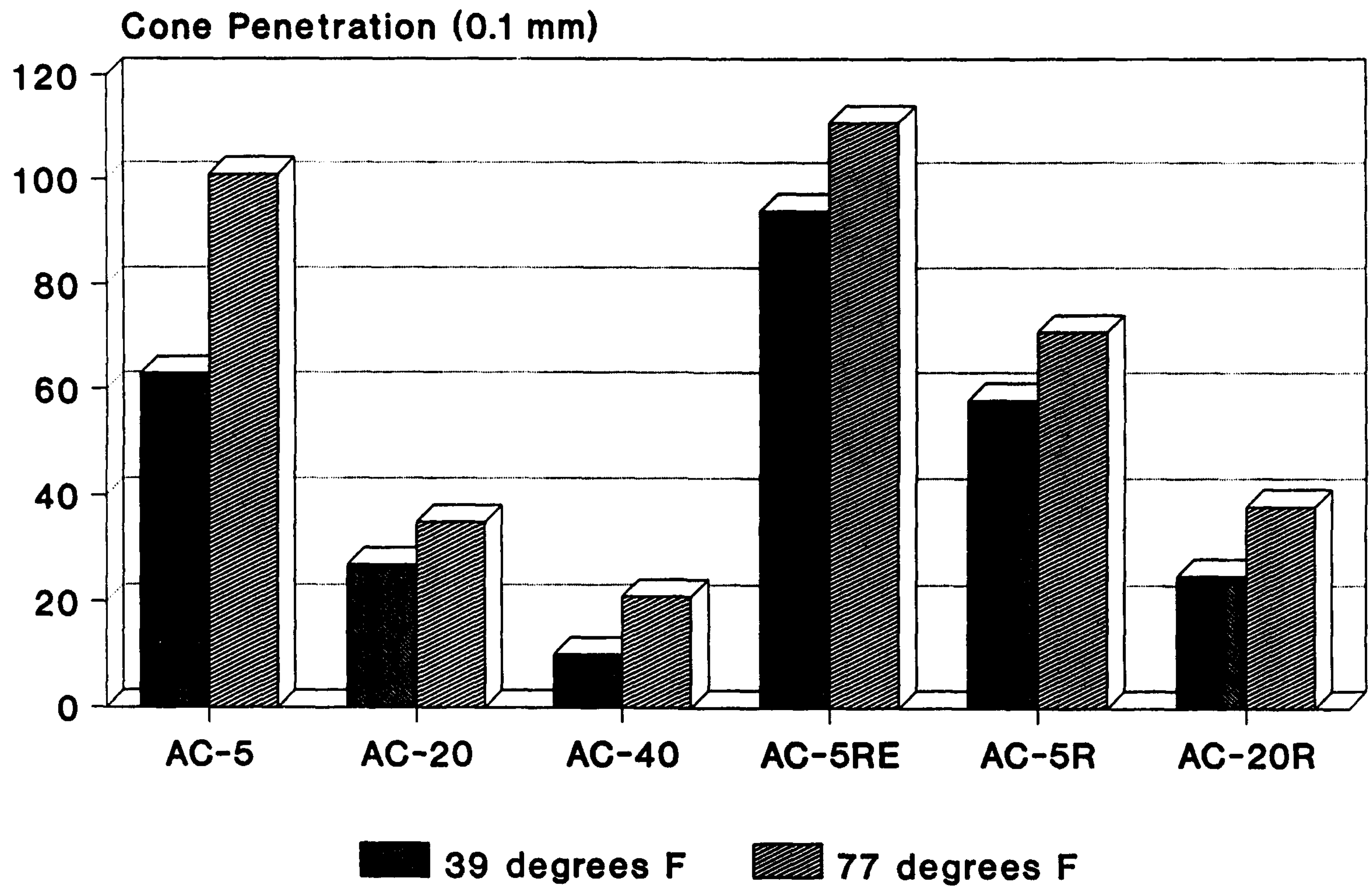

Figure 26. Cone penetration test results

A normal test is one in which the material between the two clips pulls out to a point or thread until rupture occurs at the point where the thread has practically no cross-sectional area.

Softening Point

66. The results of the ring and ball softening point test in Figure 27 display one of the most important benefits that an asphalt rubber binder can provide for a PFC pavement. The softening point of the AC-5RE was 21°F higher than its base AC-5 asphalt cement, and the AC-5R tested 31°F higher than the AC-5. The AC-20R binder's softening point was 22°F higher than its base asphalt, the AC-20. The increased softening points of the asphalt rubber binders would be significant for PFC pavements subjected to high ambient temperatures. It is well within reason for summer pavement temperatures to reach the 120°F to 130°F range in many parts of the United States. The higher softening points of the asphalt rubber binders represent a reduced chance for an unstable PFC mixture during the summer months. It is also noteworthy that the softening point of the lowest viscosity asphalt rubber examined is near the softening point of the highest viscosity asphalt cement examined (AC-5RE versus AC-40).

Resiliency

67. The resiliency test was used in this study as a measure of the test binders' capacity for elastic recovery after forced deformation. The dead weight of the loading arm (75 g) is left on the sample when measuring this recovery to simulate permanent deformation confinement, such as found in a pavement rut. The results of this test are shown in Figure 28. Negative percent rebound in this figure means that the sample continued to deform under the dead weight of the loading arm during the two minute recovery phase (i.e., the binder's elastic recovery potential was exceeded by the confining load). A positive percent rebound means that a portion of the penetration (or deformation) depth was recovered by an elastic response during the 2 min recovery phase.

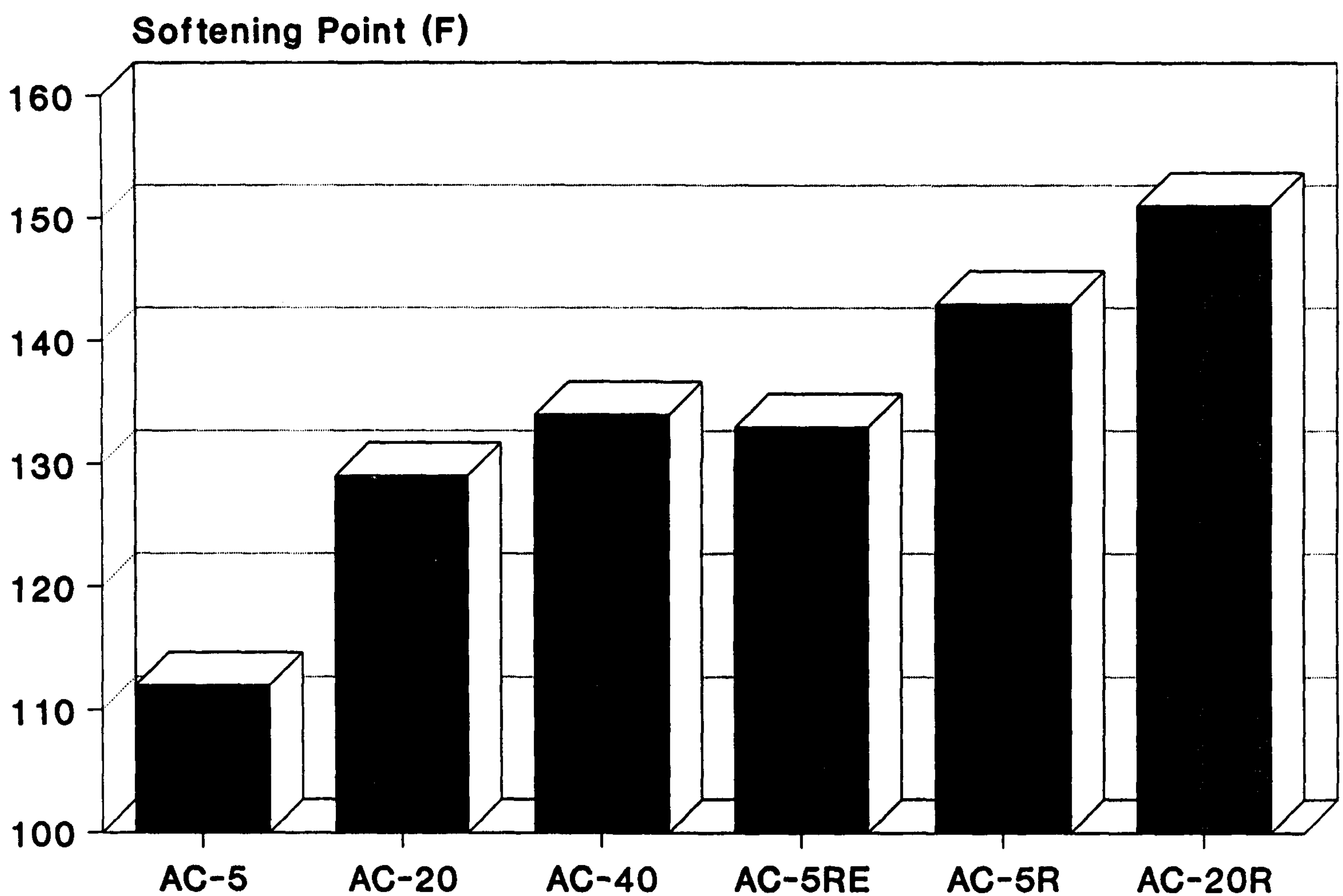

Figure 27. Ring and ball softening point test results

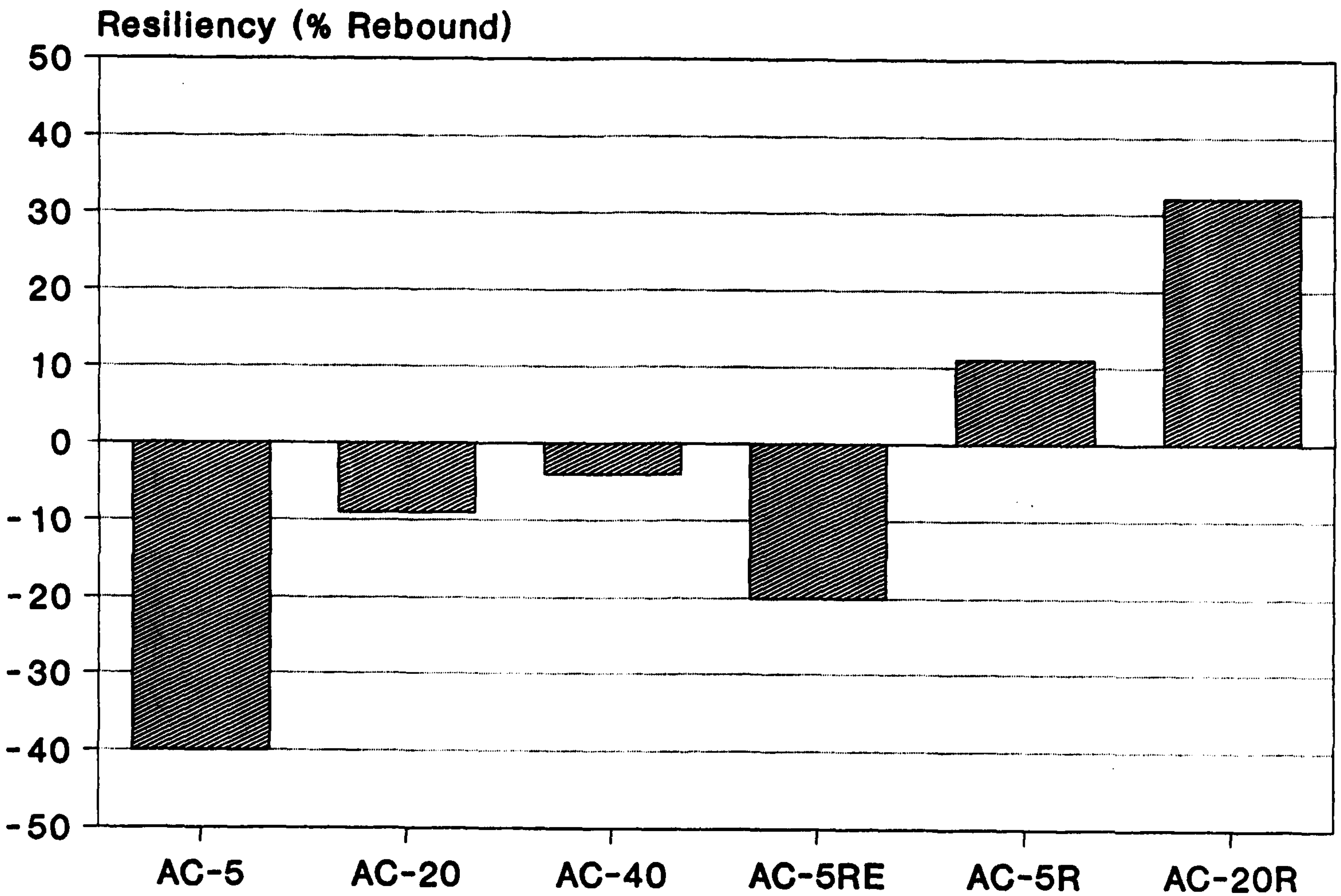

Figure 28. Resiliency test results

68. As evidenced by the data displayed in Figure 28, the AC-5, AC-20, AC-40, and AC-5RE binders did not possess enough elastic recovery potential to override the dead weight of the loading arm. These binders all continued to deform under this load. The AC-5R and AC-20R did exhibit enough elastic recovery potential to rebound at least some percentage of the imposed deformation. There is not enough experience with this test to confidently say that there is a significant difference between the test results of the AC-5R and the AC-20 or AC-40 binders. It can be said, however, that this test indicates a greater elastic recovery potential for the AC-5R and AC-20R binders in comparison with their unmodified binder counterparts.

PART VI: PHASE II, PRESENTATION AND ANALYSIS OF DATA

69. The results of the Phase II laboratory tests are presented and discussed in this part of the report. This portion of the laboratory study focused on the effects of aging on the test binders' physical properties. Two methods of laboratory accelerated aging were used in this study: the thin film oven test (TFOT) and the weatherometer. The thin film oven test was used to simulate the short-term age-hardening caused by the high mixing temperatures of the asphalt mixing plant. The weatherometer was used to simulate the aging process that a binder undergoes once it is placed in the field and exposed to the harmful effects of the environment. Two exposure periods were used with the weatherometer to represent short- and long-term environmental aging.

70. Three of the Phase I binder tests were conducted on the aged binder specimens, and the results of these tests were compared with the Phase I test results to determine the aging effects on the binders' physical properties. These three binder tests included the 140°F absolute viscosity, needle penetration, and softening point tests. Also, the percent weight loss caused by each aging process was measured to determine the amount of volatiles lost during aging. The ductility test was removed from the Phase II test plan after it was discovered during the Phase I binder tests that the physical makeup of the asphalt rubber binders make them unsuitable for ductility testing. The results of all Phase II accelerated aging tests are listed in Table 4. The results from each of the binder tests are analyzed separately in the remaining sections.

Aged Viscosity

71. The results of the aged viscosity tests are shown in Figure 29. As indicated, the thin film oven test and weatherometer aging process all had similar effects on the viscosity of each test binder. The thin film oven aged viscosity was approximately double that of the original viscosity for the AC-5, AC-20, AC-40, and AC-5RE binders. For the AC-5R and AC-20R binders, the viscosity increase was 34 percent and 48 percent, respectively. The 1 day (or

short-term) weatherometer aging process produced about a 25 percent increase in viscosity for the AC-5 and AC-5R binders, and an increase of about 10 percent for the AC-20 and AC-20R binders. The viscosity of the AC-40 increased by about 6 percent after short-term weatherometer aging. The viscosity of the AC-5RE increased by about 85 percent after short-term weatherometer aging. Only slight increases in viscosity were noted between the 1 day and 8 day weatherometer aged samples.

72. These comparisons indicate that the viscosity increases of the asphalt rubber binders tend to mirror the increases of their respective unmodified base asphalts with a few notable exceptions. The AC-5R and AC-20R TFOT aged samples resulted in viscosity increases of about half that of their respective unmodified base asphalts. This means that these asphalt rubber

Table 4

Phase II Accelerated Aging Test Results

Test	AC-5	AC-20	AC-40	AC-5RE	AC-5R	AC-20R
140°F Viscosity (P)						
Original	654	2,390	4,575	2,027	3,221	5,773
TFOT Residue *	1,196	4,169	8,532	4,189	4,302	8,535
WO Res. 1 day **	814	2,709	4,872	3,766	4,075	6,252
WO Res. 8 days	984	2,983	5,453	3,837	4,158	6,330
77°F Penetration (0.1mm)						
Original	114	44	27	85	125	40
TFOT Residue	74	29	20	67	102	36
WO Res. 1 day	89	37	21	68	105	42
WO Res. 8 days	75	35	23	60	99	38
Softening Point (°F)						
Original	112	129	134	143	133	151
TFOT Residue	117	131	138	147	132	148
WO Res. 1 day	115	130	136	149	134	149
WO Res. 8 days	120	132	139	146	137	154
Weight Loss (%)†						
TFOT Residue	0.45	0.14	0.16	0.82	1.04	0.53
WO Res. 1 day	-0.06	-0.04	-0.05	-0.01	-0.01	-0.07
WO Res. 8 days	-0.42	-0.40	-0.20	-0.08	-0.01	-0.16

* TFOT represents thin film oven test aging.

** WO represents weatherometer aging.

† Negative weight loss represents weight gain.

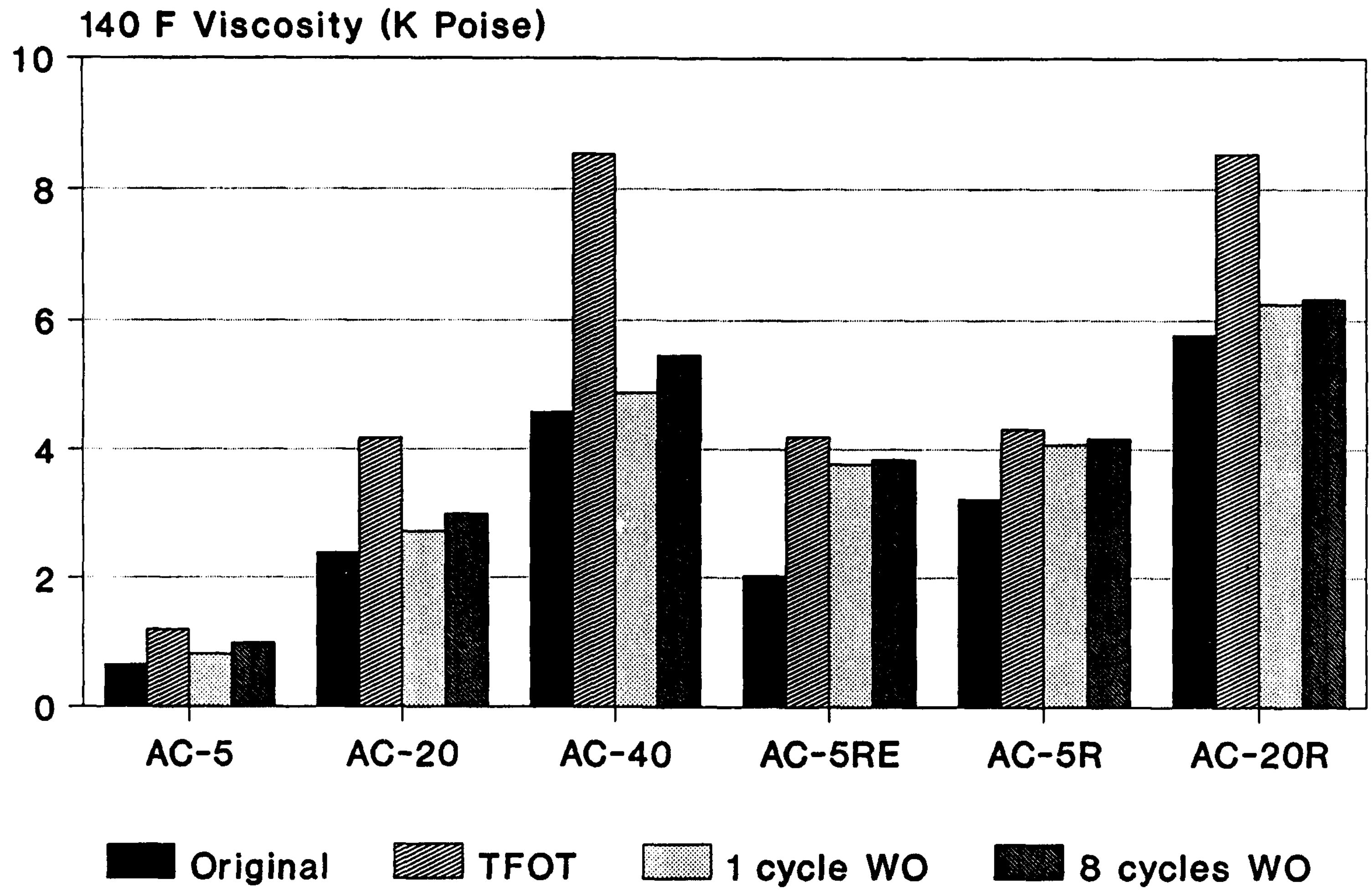

Figure 29. Aged viscosity test results

binders should age harden about 50 percent less than typical asphalt cements during asphalt plant mixture production. Also, the test results indicate that the AC-5RE binder may be susceptible to early environmental age hardening due to the extender oil in the binder.

73. To further describe the aging effects on binder viscosity, an aging index was calculated using the following equation:

$$\text{Aging Index} = \frac{\text{viscosity of TFOT aged binder}}{\text{viscosity of original binder}} \qquad (1)$$

A higher aging index value represents a higher tendency to age harden when exposed to high plant mix temperatures. The thin film oven data are used in this equation since this test represents the most severe age hardening process and because it is the most recognized laboratory aging test used in the asphalt industry. A summary of the aging index values resulting from these tests is given in Table 5.

74. The aging index values of Table 5 indicate that the addition of crumb rubber to an asphalt binder will reduce the binder's tendency to age harden at the asphalt plant. The exception to this statement may be when an extender oil is added with the crumb rubber such as found in the AC-5RE binder. An asphalt rubber supplier would be expected to realize that an extender oil loses some of its effectiveness when subjected to high temperatures, and a simple overdosage of extender oil would likely be used to counteract this loss.

Table 5

Aging Index Values of TFOT Aged Binders

Binder	Aging Index
AC-5	1.83
AC-20	1.74
AC-40	1.86
AC-5RE	2.07
AC-5R	1.33
AC-20R	1.48

Aged Penetration

75. The results of the aged penetration tests are shown in Figure 30. As with the aged viscosity tests, the asphalt rubber binders change in penetration after aging closely mirrors the respective base asphalt response to the same aging conditions. When comparing the aged penetration values of the AC-5RE and AC-5R binders to the AC-5 binder, it can be said that the asphalt rubber binders reduced the aging effects to a degree. Also, the AC-20R showed virtually no penetration loss for all accelerated aging processes, whereas the AC-20 binder did lose some of its penetration value during all of the aging processes. Even the low penetration AC-40 asphalt cement showed signs of age-hardening in these tests.

76. Similar to the aged viscosity analysis, the original and TFOT penetration values were used to calculate the magnitude of aging for each test binder. The amount of aging in this instance is called the percent retained penetration and is calculated using the following equation:

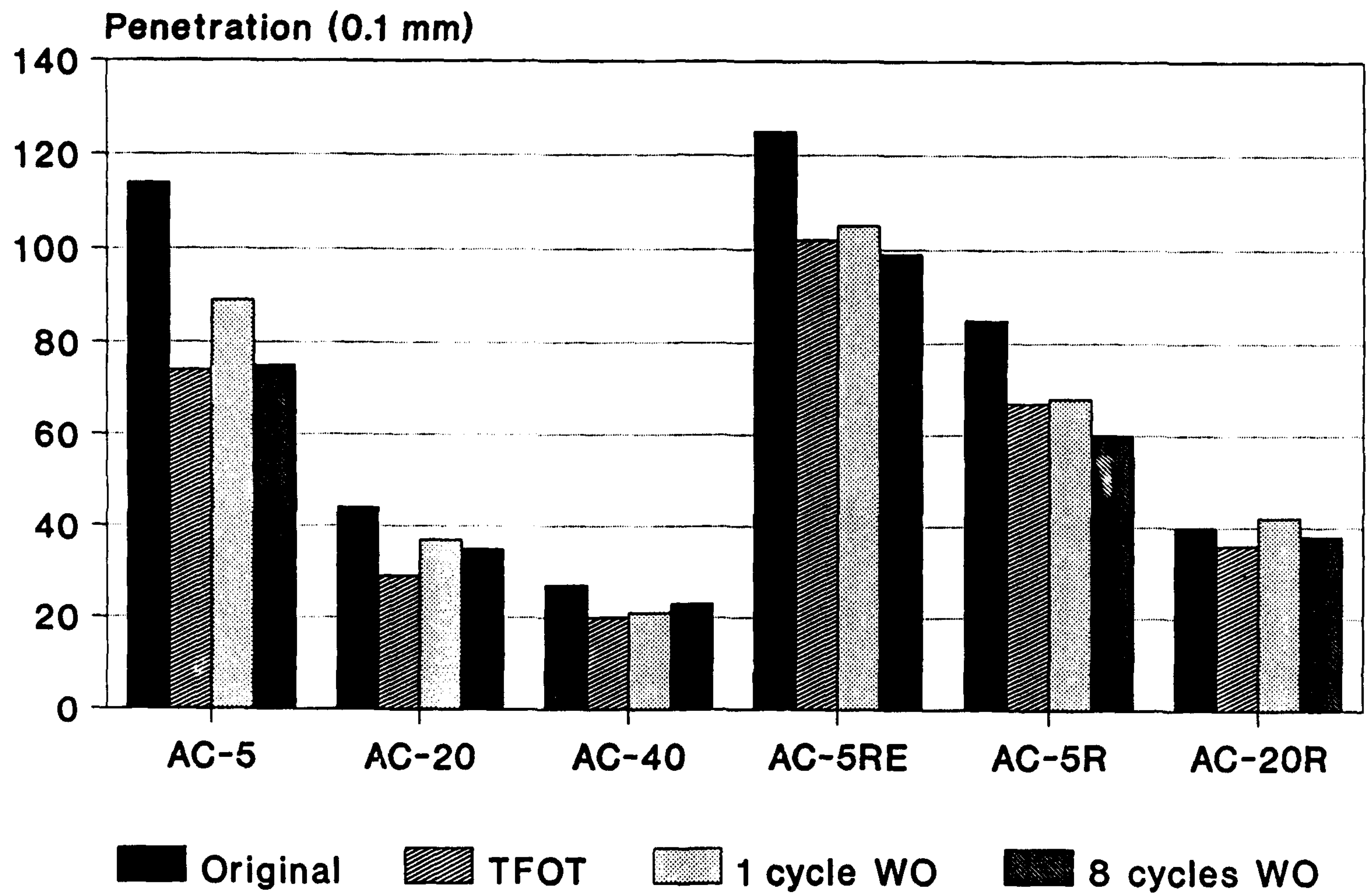

Figure 30. Aged penetration test results

$$\text{Percent Retained Penetration} = \frac{\text{penetration of TFOT aged binder}}{\text{penetration of original binder}} \times 100 \quad (2)$$

A higher retained penetration is desired since it represents a lower tendency to age-harden when exposed to high temperatures. The percent retained penetration values calculated for these tests are summarized in Table 6.

Table 6

Percent Retained Penetration Values of Thin Film Oven Aged Binders

Binder	Retained Penetration (percent)
AC-5	64.9
AC-20	65.9
AC-40	74.1
AC-5RE	78.8
AC-5R	81.6
AC-20R	90.0

77. The percent retained penetration values of Table 6 clearly indicate the asphalt rubbers reduced aging tendencies as measured by the penetration test. These values support the same conclusions reached in the aged viscosity analysis when the aging index values also indicated a reduced early age-hardening potential for the asphalt rubber binders.

Aged Softening Point

78. The ring and ball softening point test was included in the accelerated aging analysis to determine if the laboratory aging processes would significantly increase the binders solid to liquid transition temperature. Any excessive increases in softening point could be used to indicate a potentially brittle, age-hardened binder. The results of these

tests, as shown in Figure 31, indicate that the softening point was virtually unchanged by all aging processes for all of the test binders. Most asphalt field practitioners would agree that asphalt binders are generally more susceptible to softening at high temperatures earlier in their service life rather than after they have been age hardened by excessive heat or the environment. This would indicate that the softening point test is not affected by the aging processes used in this study.

Percent Weight Loss

79. The weight loss measurements made on each test binder after laboratory aging provided some unexpected results. First, all of the test binders absorbed enough water during the rain simulation cycles in the weatherometer to undergo a weight gain during the aging process. The amount of water absorbed could not be correlated to field conditions because the laboratory sample thickness (3/8 in.) was much greater than even a heavy film thickness on an aggregate in a PFC mixture (about 10 microns). Since the amount of water absorption could not be separated from the amount of weight loss due to vaporization of the binder's lighter constituents, the weight loss data of the weatherometer-aged samples were useless for this analysis.

80. The weight loss results from the TFOT-aged samples did fall within the expected range of weight loss percentages, but the comparative data ranges of the asphalt rubber binders and the asphalt cement binders were unexpected. As seen in Figure 32, the weight loss of the asphalt rubber binders were two to four times that of their respective base asphalts after thin film oven aging. A sizable portion of the AC-5RE weight loss can be attributed to the vaporization of some extender oil. It is also theorized that a small percentage of the petroleum-based oil found in the tire rubber was vaporized in the thin film oven, causing further weight loss in the asphalt rubber binders. Regardless of the reason for the asphalt rubber binders higher weight loss, the magnitude of the weight loss did not seem to be significant enough to detrimentally affect the aged viscosity or penetration properties.

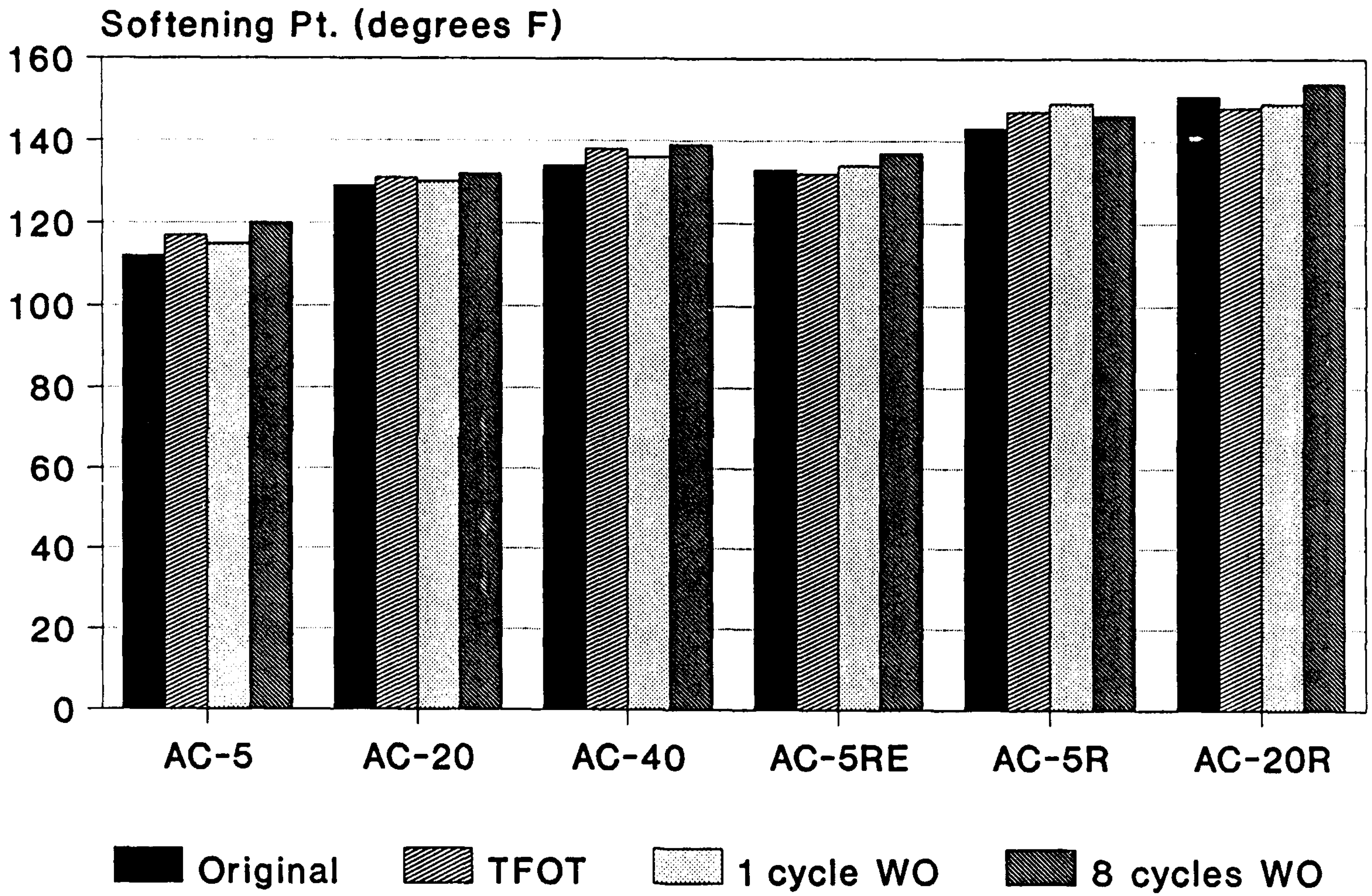

Figure 31. Aged softening point test results

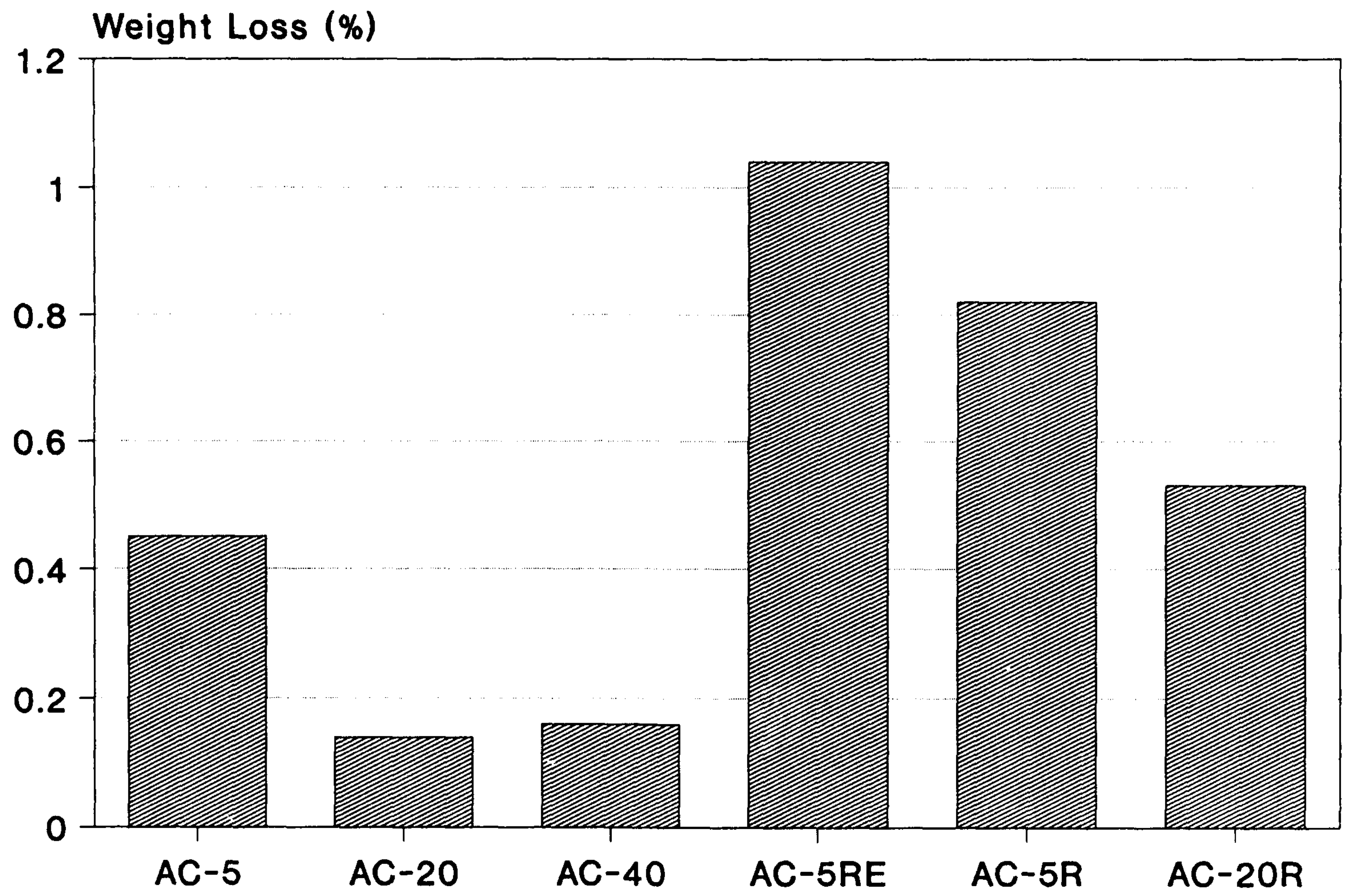

Figure 32. Thin-film oven test percent weight loss results

PART VII: PHASE III, PRESENTATION AND ANALYSIS OF DATA

81. The results of the Phase III laboratory tests are presented and discussed in this part of the report. The Phase III tests of this laboratory study included tests on laboratory produced open-graded asphalt concrete mixtures made with the six test binders. A mix design analysis was conducted to evaluate the effects of asphalt rubber binders on PFC mixture voids and density properties. A proposed method of estimating the optimum binder content for an asphalt rubber PFC mixture was also evaluated in the mix design tests. Additional open-graded mixture tests included a binder drain off test, a permeability test, and three different stripping tests. All of these tests were designed to evaluate the effects of asphalt rubber binders on those physical properties critical to PFC field performance.

82. The same six test binders used during Phases I and II of this study were evaluated in each of the Phase III open-graded mixture tests. All of the aggregates used in these tests were crushed granite from a Watsonville, California quarry. The granite aggregates had an apparent specific gravity of 2.84 and water absorption percentages of 2.0 and 3.0 for the course and fine aggregate material, respectively. The granite aggregates had fractured and angular faces, which are important qualities for a PFC mixture. A single aggregate gradation was used throughout the Phase III tests to decrease the gradation effect on the open-graded mixture test results. The 3/4 in. maximum aggregate size gradation specified by the US Army Corps of Engineers guide specification on PFC's was selected as the target aggregate gradation (Headquarters, Department of the Army 1984). The recommended gradation limits of this specification and the target gradation or job mix formula (JMF) used throughout the Phase III tests are shown in Table 7 and Figure 33.

Table 7

Open-Graded Mixture Aggregate Gradation

U.S. Standard Sieve Size	CEGS-02562 Recommended Limits	JMF
3/4 in.	100	100
1/2 in.	70-100	85
3/8 in.	45-75	60
No. 4	25-40	33
No. 8	10-20	15
No. 30	3-10	7
No. 200	0-5	3

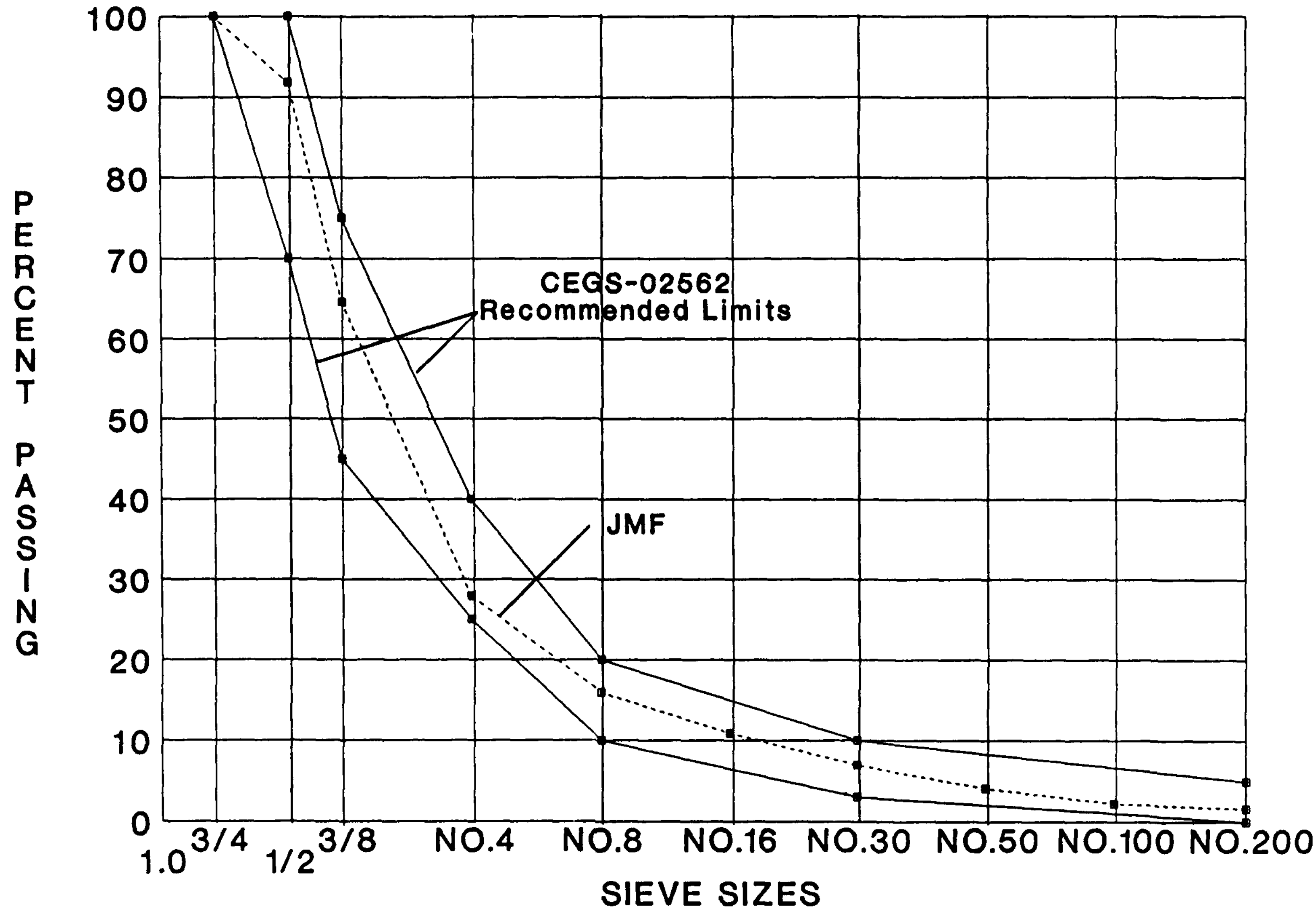

Figure 33. Open-graded mixture aggregate gradation curves

Mix Designs

83. The mix design tests began with an analysis of the widely used CKE Method of determining optimum binder contents for PFC mixtures. The CKE test method produces a percent oil retained value for a given aggregate source, and a graphical relationship between this value and a surface constant (K_c) is used to determine the K_c value. The K_c value is then used in Equation 3 to determine the estimated optimum binder content (percent by weight) for the given aggregate:

$$\text{Optimum Binder Content (OBC)} = (K_c \times 2.0) + 4.0 \qquad (3)$$

84. Since the standard CKE method of determining OBC for PFC mixtures does not consider binder viscosity, Equation 3 may theoretically underestimate the OBC for high viscosity binders such as asphalt rubber. A conservative approach to correcting this discrepancy for asphalt rubber binders would be to factor out the rubber particles contained in the binder and consider them as aggregates rather than part of the binder system. This is done by dividing the standard CKE equation by the percentage of the asphalt rubber binder that is asphalt cement. Thus, if the AC-5RE binders 16 percent rubber and 5 percent extender oil is equated with the 17 percent rubber AC-5R and AC-20R binders for convenience sake, the new CKE equation for the asphalt rubber binders of this study becomes:

$$\text{OBC} = \frac{(K_c \times 2.0) + 4.0}{1 - \text{percent rubber}} \qquad (4)$$

or

$$\text{OBC} = \frac{(K_c \times 2.0) + 4.0}{1 - .17} = \frac{(K_c \times 2.0) + 4.0}{0.83}$$

85. The CKE test was conducted in the laboratory on a sample of the aggregates used in this phase of the study, and the result was a percent oil

retained value of 2.7. This value was corrected for the standard aggregate specific gravity of 2.65 by the following equation:

$$\text{Corrected Percent Oil Retained} = \text{Percent Oil Retained} \times \frac{\text{specific gravity of aggregate}}{2.65} \qquad (5)$$

For the aggregates used in this study, the corrected value then becomes:

$$\text{Corrected Percent Oil Retained} = 2.7 \times \frac{2.84}{2.65} = 2.9$$

86. The corrected value of 2.9 percent oil retained was then used with the graph in Figure 34 to determine a surface area constant (K_c) value of 1.3. This K_c value of 1.3 was then used with both the standard CKE equation for estimating OBC (Eq. 3) and the modified equation for the asphalt rubber binders (Eq. 4). This resulted in the following calculations:

Standard CKE equation:

$$\begin{aligned} OBC &= (K_c \times 2.0) + 4.0 \\ &= (1.3 \times 2.0) + 4.0 \\ &= 2.6 + 4.0 \\ &= 6.6\% \end{aligned}$$

Modified CKE equation:

$$\begin{aligned} OBC &= \frac{(K_c \times 2.0) + 4.0}{0.83} \\ &= (6.6)/(0.83) \\ &= 8.0\% \end{aligned}$$

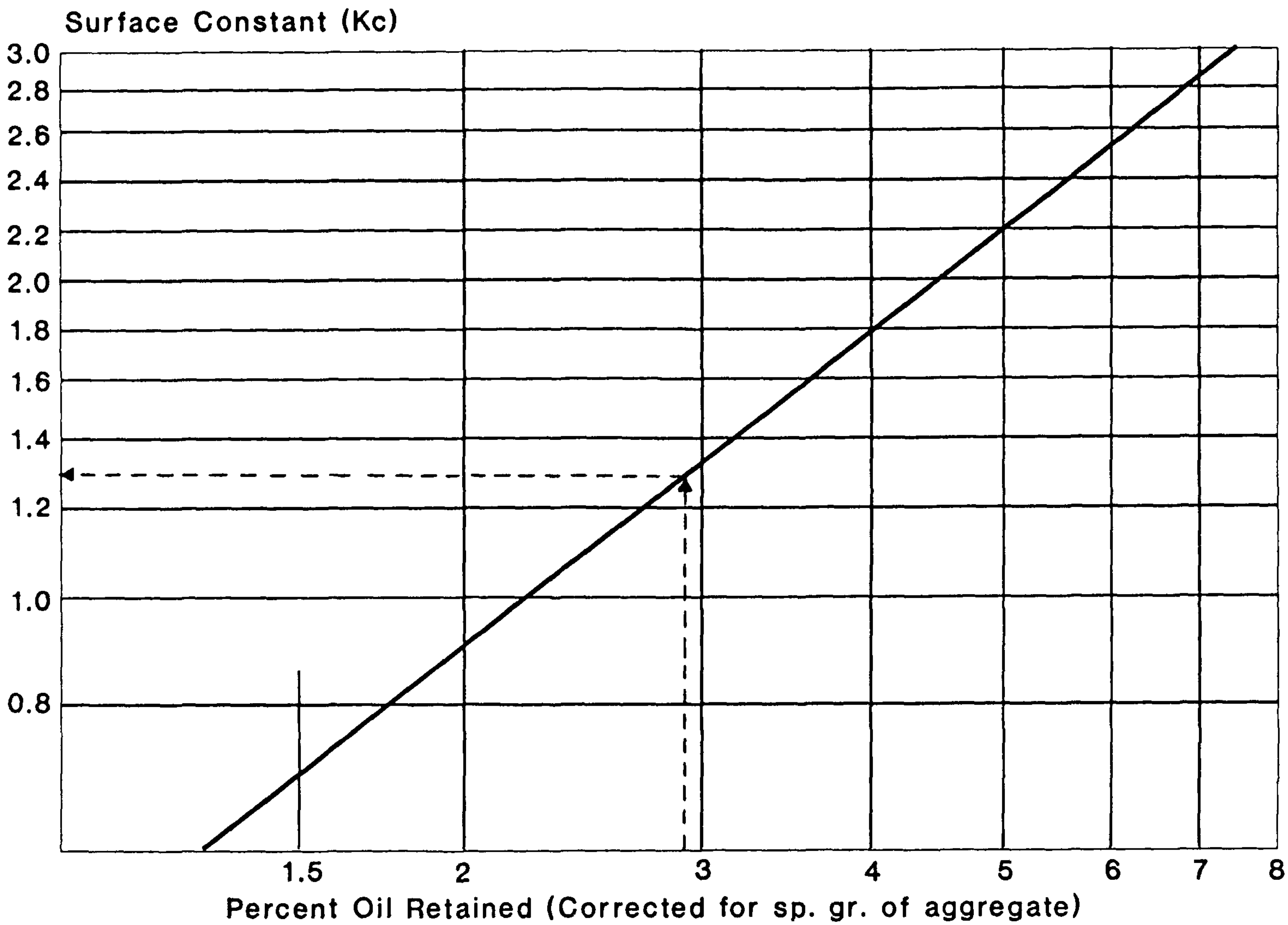

Figure 34. Chart for determining K_c from aggregate absorption

87. To evaluate both of these OBC estimates with all six of the test binders, the following binder contents were used in the 6-in.-diam laboratory open-graded mixture specimens: 6.6, 7.6, and 8.6 percent. Any significant over-saturation of the open-graded mixtures would be determined by evaluating the specimen's total voids and voids filled data. Unit weight (or density) measurements were made to detect any possible negative effects on compaction caused by the presence of rubber or by high binder contents. The results of these measurements on the Marshall hand hammer compacted specimens (25 blows on one side) are shown in Table 8.

Table 8

Open-Graded Mix Design Data

Binder	Binder Content percent	Total Voids percent*	Voids Filled percent**	Unit Weight pcf
	6.6	22.0	43.6	119.0
AC-5	7.6	20.8	45.4	116.7
	8.6	17.2	50.3	113.6
	6.6	24.9	36.7	115.2
AC-20	7.6	22.2	42.1	117.1
	8.6	19.3	46.8	120.4
	6.6	26.2	32.0	115.6
AC-40	7.6	22.9	36.2	118.2
	8.6	20.0	43.5	120.9
	6.6	26.0	31.8	115.2
AC-5RE	7.6	24.5	36.2	117.8
	8.6	23.8	39.3	120.3
	6.6	26.3	31.2	117.1
AC-5R	7.6	25.7	32.2	119.2
	8.6	25.0	36.4	121.8
	6.6	27.3	30.0	117.5
AC-20R	7.6	26.9	30.9	119.8
	8.6	26.0	31.7	122.8

* Percent total voids = $\frac{\text{volume of air}}{\text{total volume}} \times 100.$

** Percent voids filled = $\frac{\text{volume of binder}}{\text{volume of binder + volume of air}} \times 100.$

88. The total voids and voids filled data are shown in Figures 35 and 36, respectively. These figures clearly show that the higher viscosity asphalt rubber binders provide the open-graded mixture with higher total voids and less voids filled. A PFC with a higher void content will have a higher water storage capacity which results in better water draining capabilities. When a binder fills less of the available void space in comparison with another binder at the same dosage rate, then more of the binder is being used to coat the aggregates, which is its intended function in a PFC mixture. As noted in Figures 35 and 36, the asphalt rubber binders were less sensitive to increases in binder content with respect to total voids and voids filled. This indicates that the 6.6 percent binder content is likely to be the OBC for the asphalt cement binders, and that the asphalt rubber binders are allowable at higher binder contents.

89. The unit weight data resulting from the mix design tests are shown in Figure 37. Although unit weight (or density) is not a specified design consideration for PFC mixtures, these data indicate that asphalt rubber binders do not hinder compaction. To the contrary, the asphalt rubber mixtures had slightly higher densities than their asphalt cement counterparts. Also evident in Figure 37 is that the AC-5 mixtures became increasingly over-saturated with binder at the 7.6 and 8.6 percent binder contents to the point of reducing the resulting mixture densities.

Binder Drain Off

90. The results of the binder drain off tests are shown in Table 9. As previously mentioned in Part III, 50 percent drainage is the maximum limit prescribed by this test to prevent detrimental binder drainage during mixing and construction. Four test temperatures were selected for this test: 250°F, 275°F, 300°F, and 325°F. The three asphalt cement binders were tested first, using the OBC derived from the standard CKE equation (Eq. 3) and binder contents at one and two percent higher than this optimum value. After conducting tests at 250°F, 275°F, and 300°F, it was apparent that excess binder drainage would likely occur in all tests at 325°F; therefore, the 325°F tests were not conducted on the asphalt cement specimens.

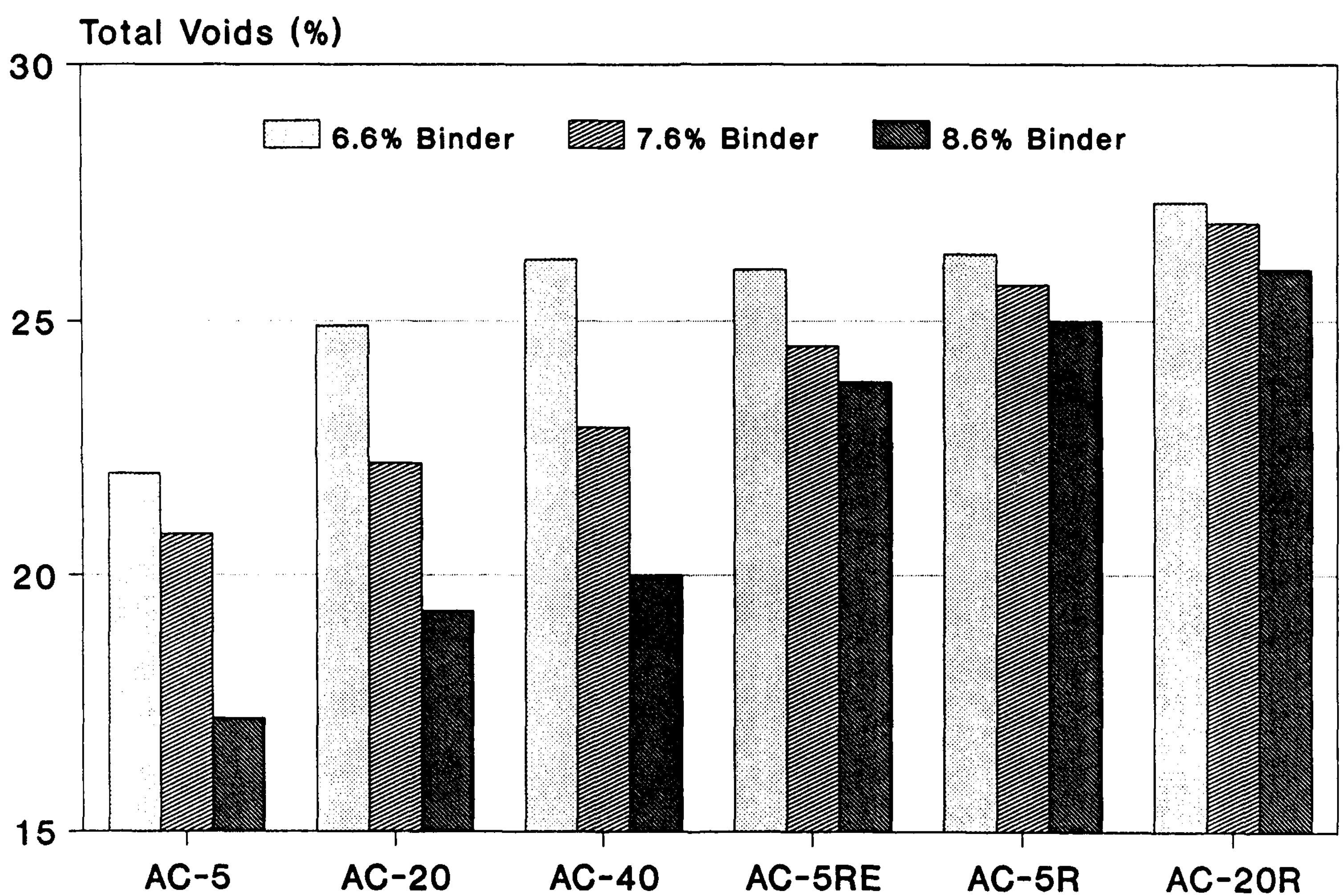

Figure 35. Percent total voids of open-graded mixture specimens

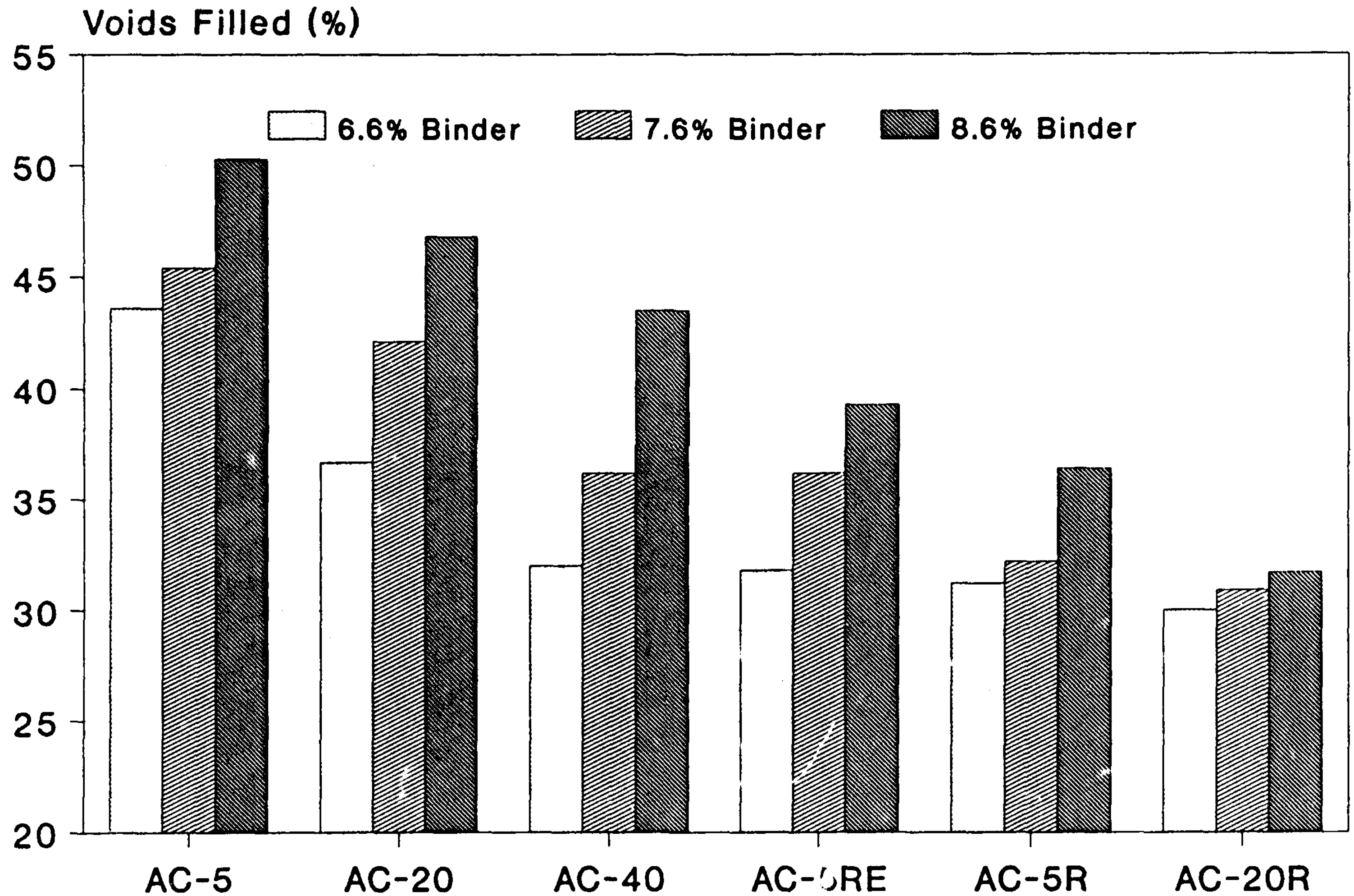

Figure 36. Percent voids filled of open-graded mixture specimens

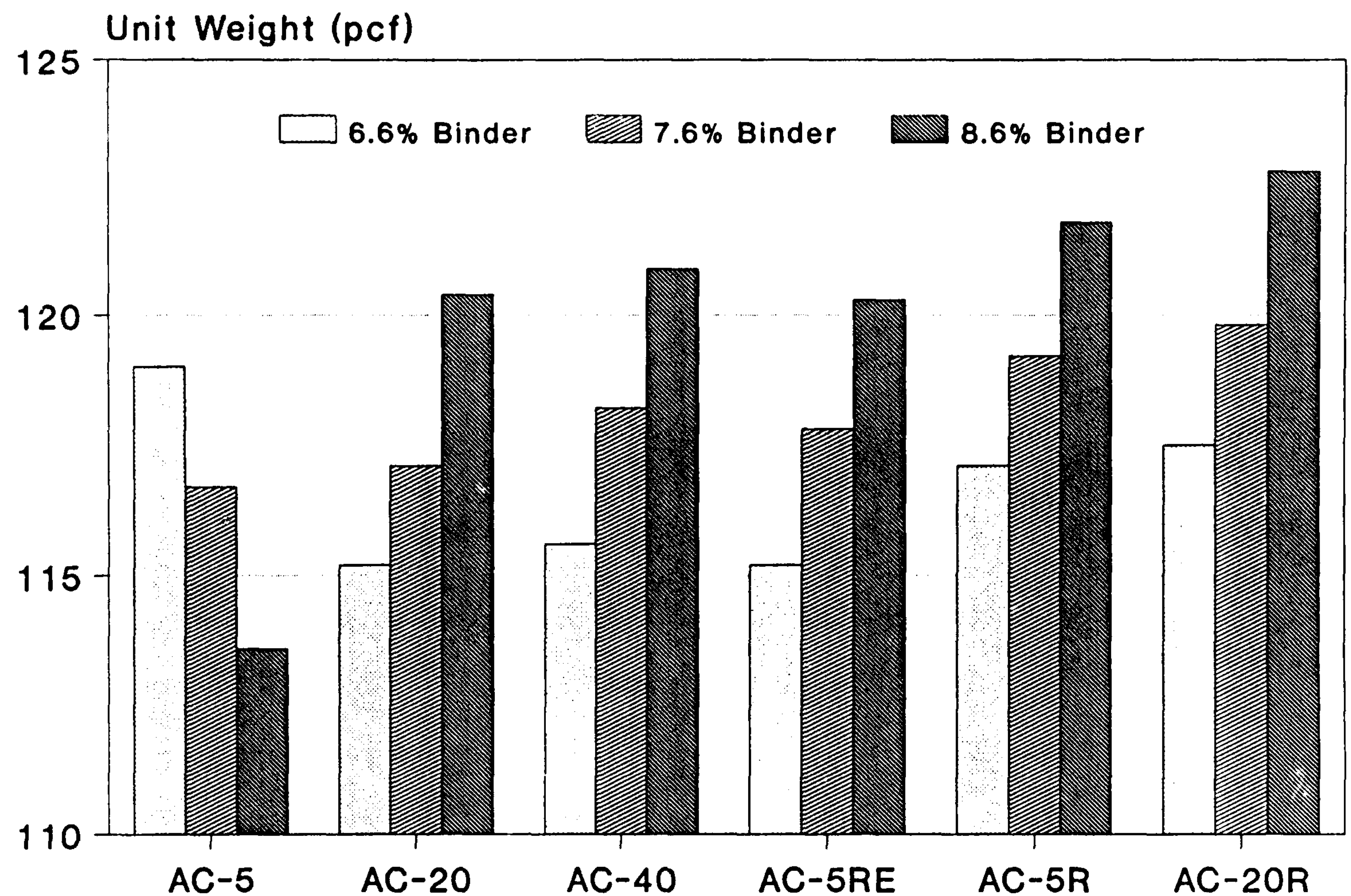

Figure 37. Unit weight of open-graded mixture specimens

Table 9

Binder Drain Off Test Results

		Percent Drainage			
Binder	Percent Binder	250°F	275°F	300°F	325°F
	6.6	10	30	70	--
AC-5	7.6	60	60	80	--
	8.6	70	80	90	--
	6.6	20	30	30	--
AC-20	7.6	50	50	50	--
	8.6	70	70	80	--
	6.6	30	40	50	--
AC-40	7.6	50	50	60	--
	8.6	60	60	80	--
	6.6	--	10	10	10
	7.6	--	10	10	10
	8.6	--	20	20	20
AC-5RE					
	8.0	--	--	10	20
	9.0	--	--	10	20
	10.0	--	--	20	40
	6.6	--	0	10	10
	7.6	--	0	10	10
	8.6	--	0	20	20
AC-5R					
	8.0	--	--	10	20
	9.0	--	--	10	30
	10.0	--	--	10	30
	6.6	--	--	0	10
	7.6	--	--	0	10
	8.6	--	--	0	30
AC-20R					
	8.0	--	--	10	10
	9.0	--	--	10	10
	10.0	--	--	30	30

91. Testing began at 275°F on the AC-5RE and AC-5R binders using the same three binder contents as for the asphalt cement specimens. After no binder drainage was noted at these binder contents on the AC-5R/275°F tests, the AC-20R tests at 275°F were canceled. The remaining asphalt rubber binder drain off tests were conducted at 300°F and 325°F with six binder contents at each test temperature. Three of the binder contents were the same as those used for the asphalt cement drain off tests, and the other three binder contents were derived in a similar fashion from the modified CKE equation (Eq. 4).

92. When the 50 percent drainage limit is applied, the data in Table 9 clearly support the 6.6 percent binder content as the optimum for the asphalt cement binders at all test temperatures. Also, the 300°F test temperature appears to be too high in terms of binder drainage. Therefore, these test results suggest a binder content at or near the 6.6 percent level and a maximum mix temperature of about 275°F for the mixing plant.

93. The test results for the asphalt rubber binders indicate that higher than normal mix temperatures do not significantly increase binder drainage, even when coupled with very high binder contents. The only test results which approached the 50 percent binder drainage limit were at the 10 percent binder content. From the perspective of binder drainage, binder contents up to and possibly above 10 percent are allowable in asphalt rubber PFC mixtures, even at high mix temperatures around 325°F. In most cases, the cost of producing such a binder-rich PFC mixture would limit the binder content before such levels were reached.

94. For comparative purposes, the test results at each test temperature are presented in Figures 38 to 41. These figures suggest that the standard CKE derived OBC's and a 275°F mixing temperature are the safe limits for the three asphalt cement binders. A significant reduction in binder drainage is also evident in Figures 38 to 41 for all asphalt rubber tests.

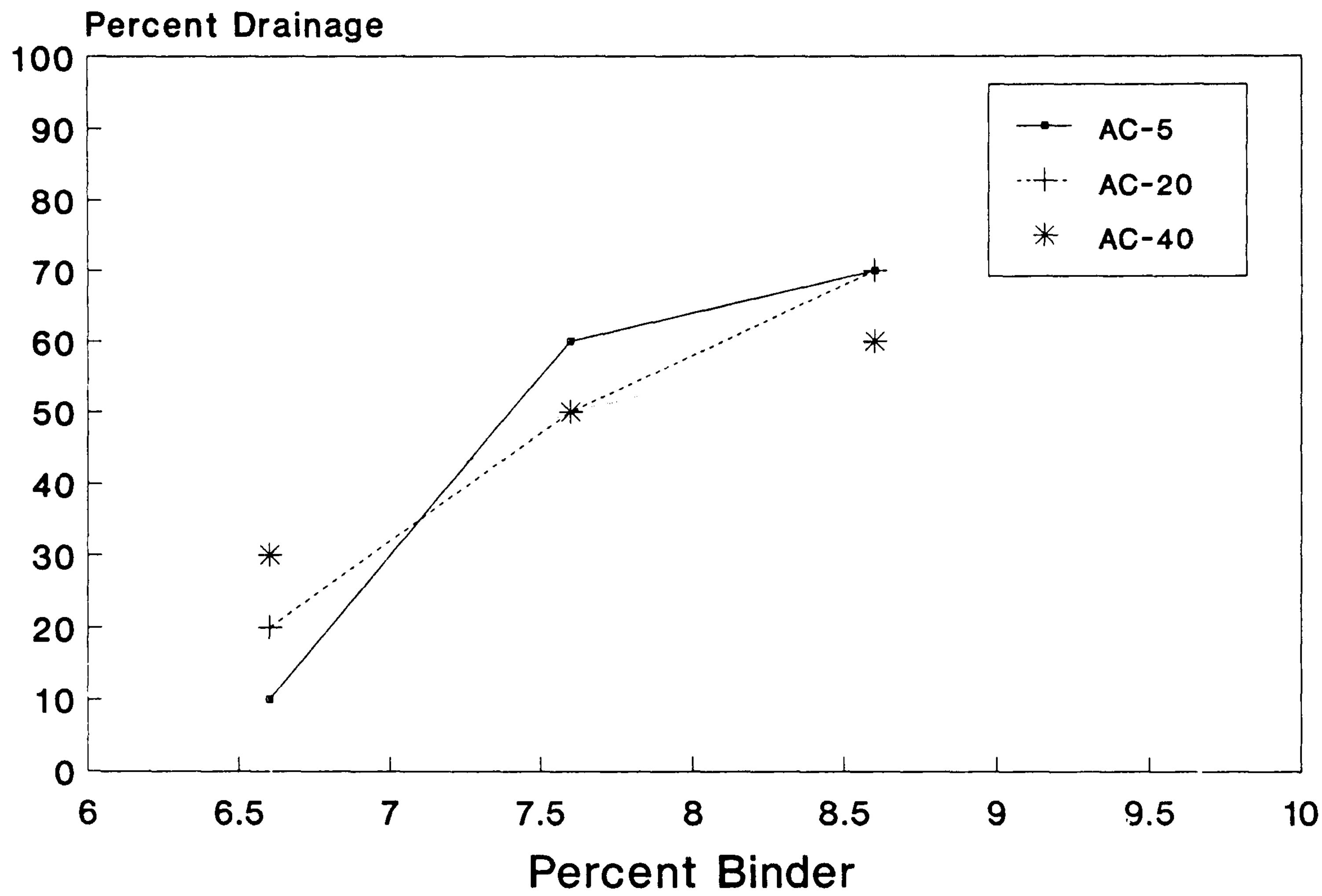

Figure 38. Binder drain off test results at 250°F

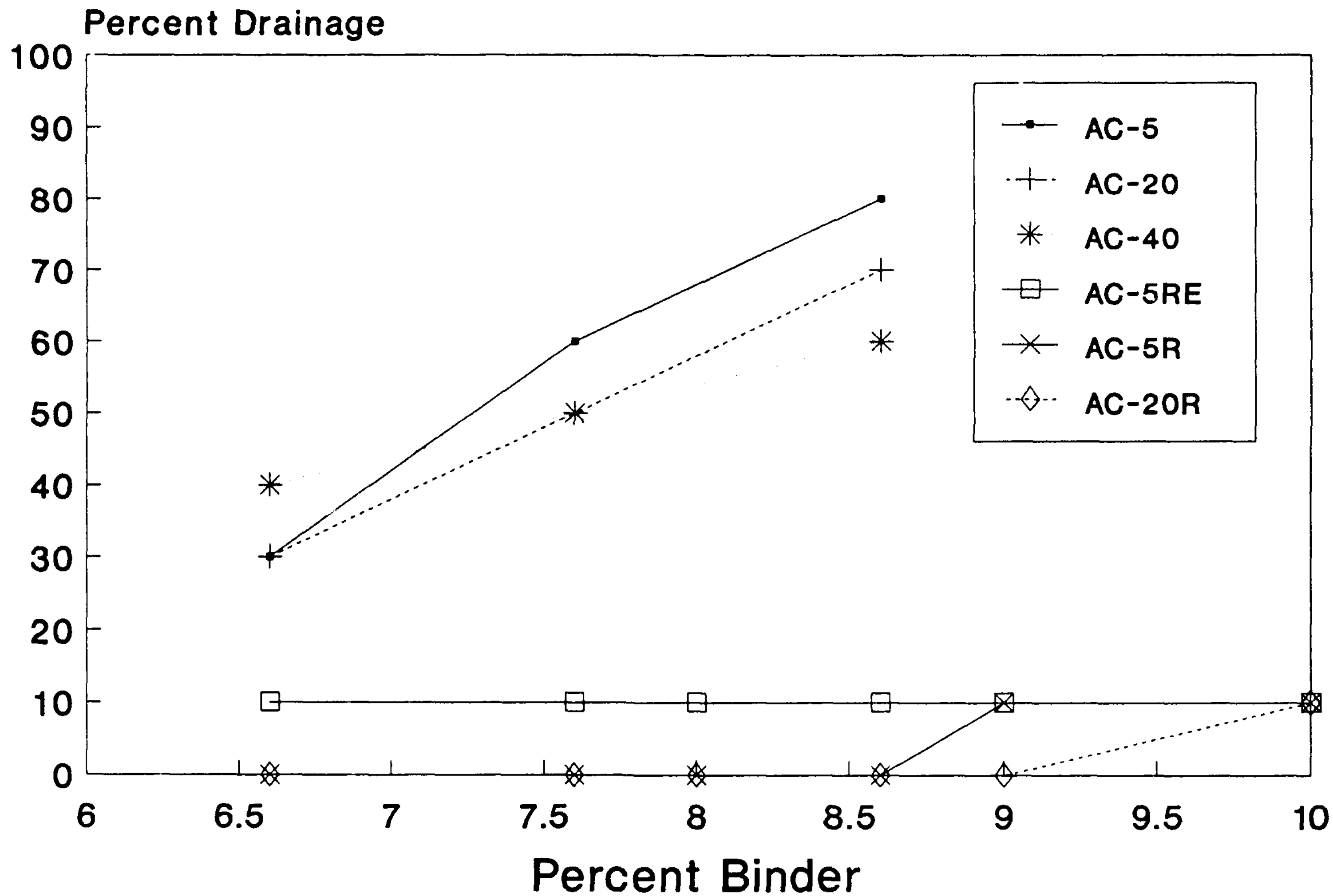

Figure 39. Binder drain off test results at 275°F

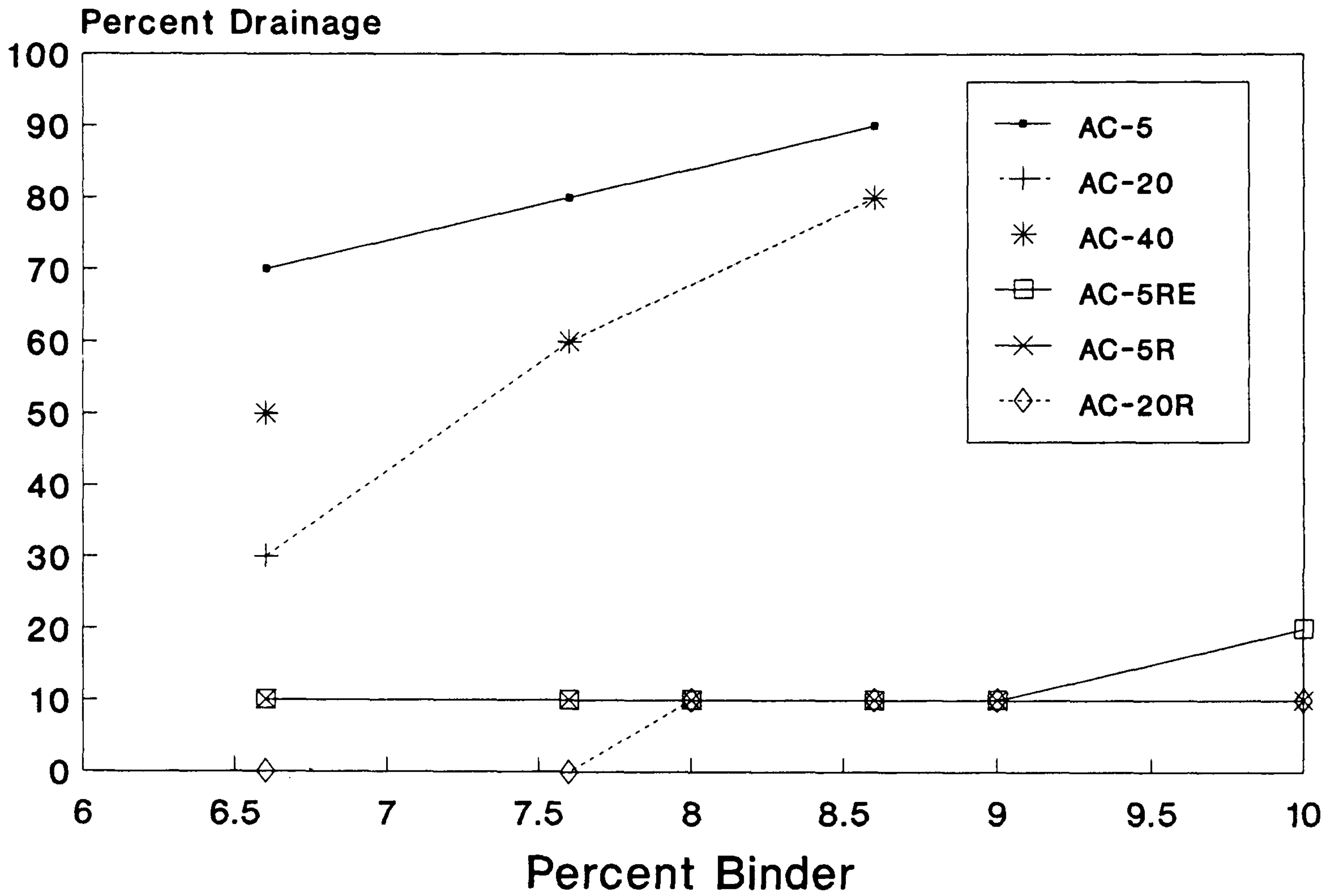

Figure 40. Binder drain off test results at 300°F

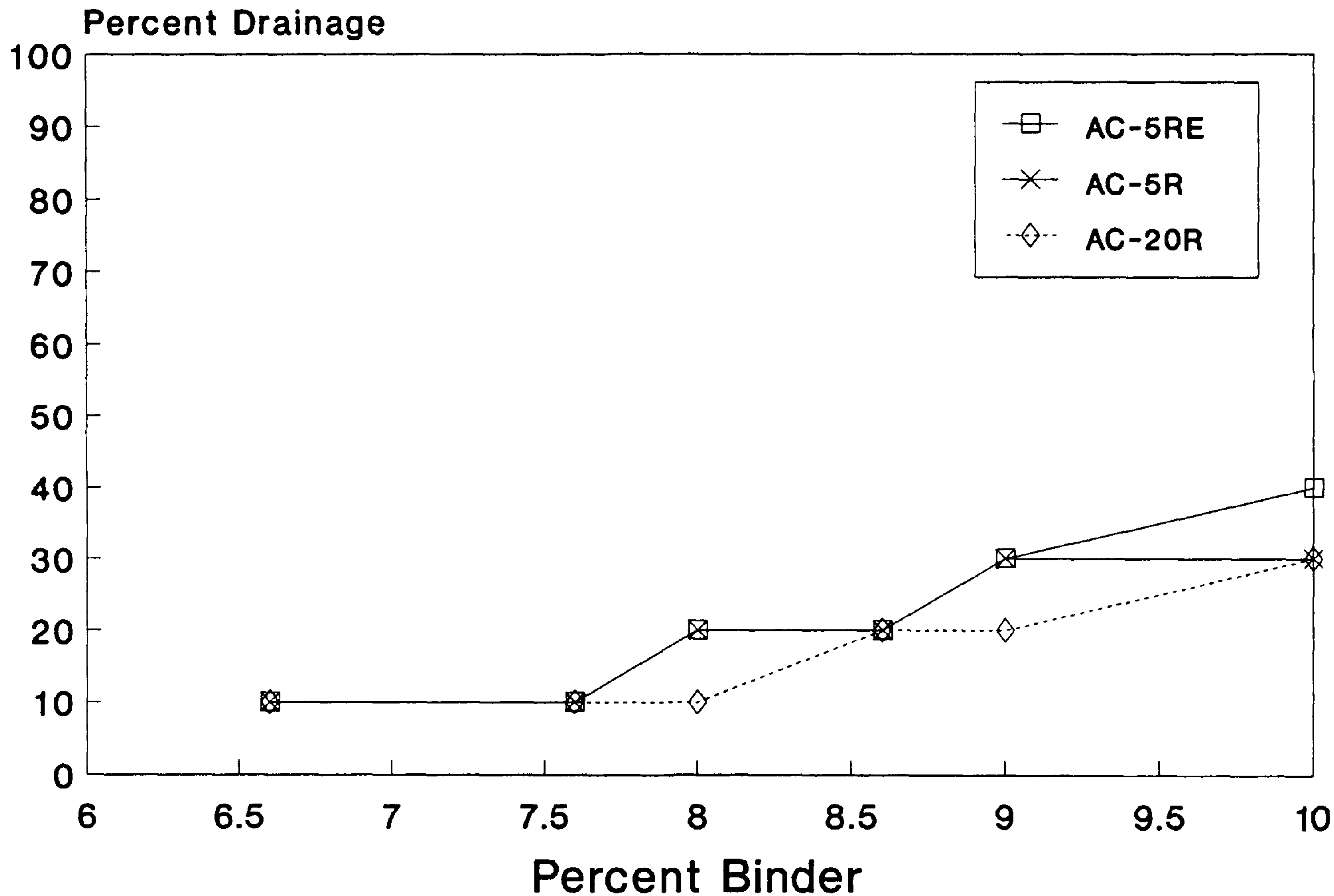

Figure 41. Binder drain off test results at 325°F

Permeability

95. Laboratory permeability tests were conducted on open-graded mixture samples made with each test binder at three binder contents. The asphalt cement samples were mixed at 275°F with binder contents of 6.6, 7.6, and 8.6 percent. The asphalt rubber samples were mixed at 300°F with binder contents of 8.0, 9.0, and 10.0 percent. The results of the permeability tests are given in Table 10. These results are also presented in Figures 42 and 43. The range of permeability values resulting from these laboratory tests is comparable to the field data collected by White (1976) in his evaluation of 17 PFC pavement sites in 1973 and 1974. The same permeability test equipment

Table 10

Permeability Test Results

Binder	Percent Binder	Flow Rate (ml/min)
AC-5	6.6	4,540
	7.6	3,356
	8.6	3,284
AC-20	6.6	5,717
	7.6	3,284
	8.6	2,490
AC-40	6.6	7,017
	7.6	6,712
	8.6	5,323
AC-5RE	8.0	4,980
	9.0	3,958
	10.0	3,958
AC-5R	8.0	7,017
	9.0	5,937
	10.0	5,146
AC-20R	8.0	7,351
	9.0	6,712
	10.0	6,432

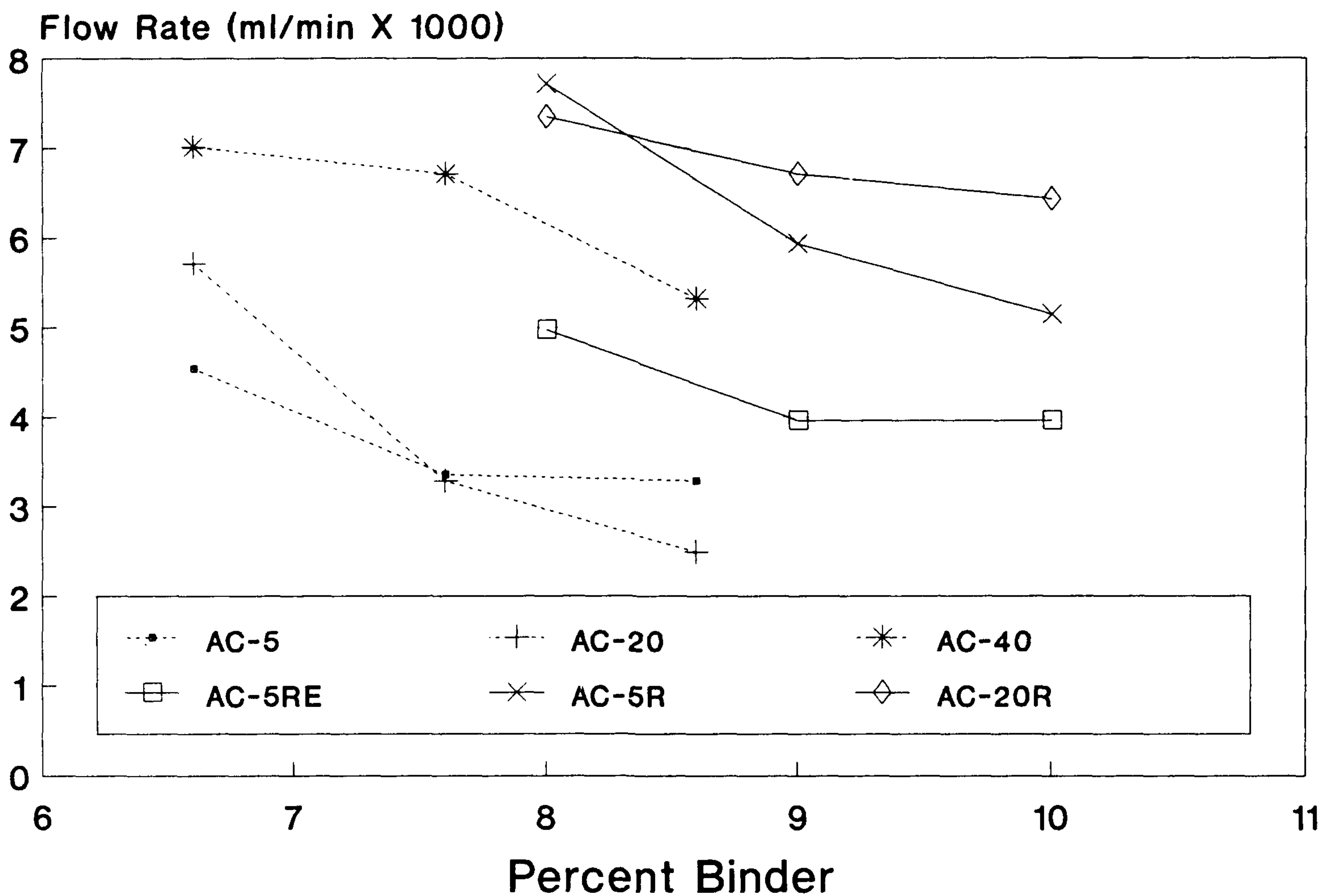

Figure 42. Line graph of permeability test results

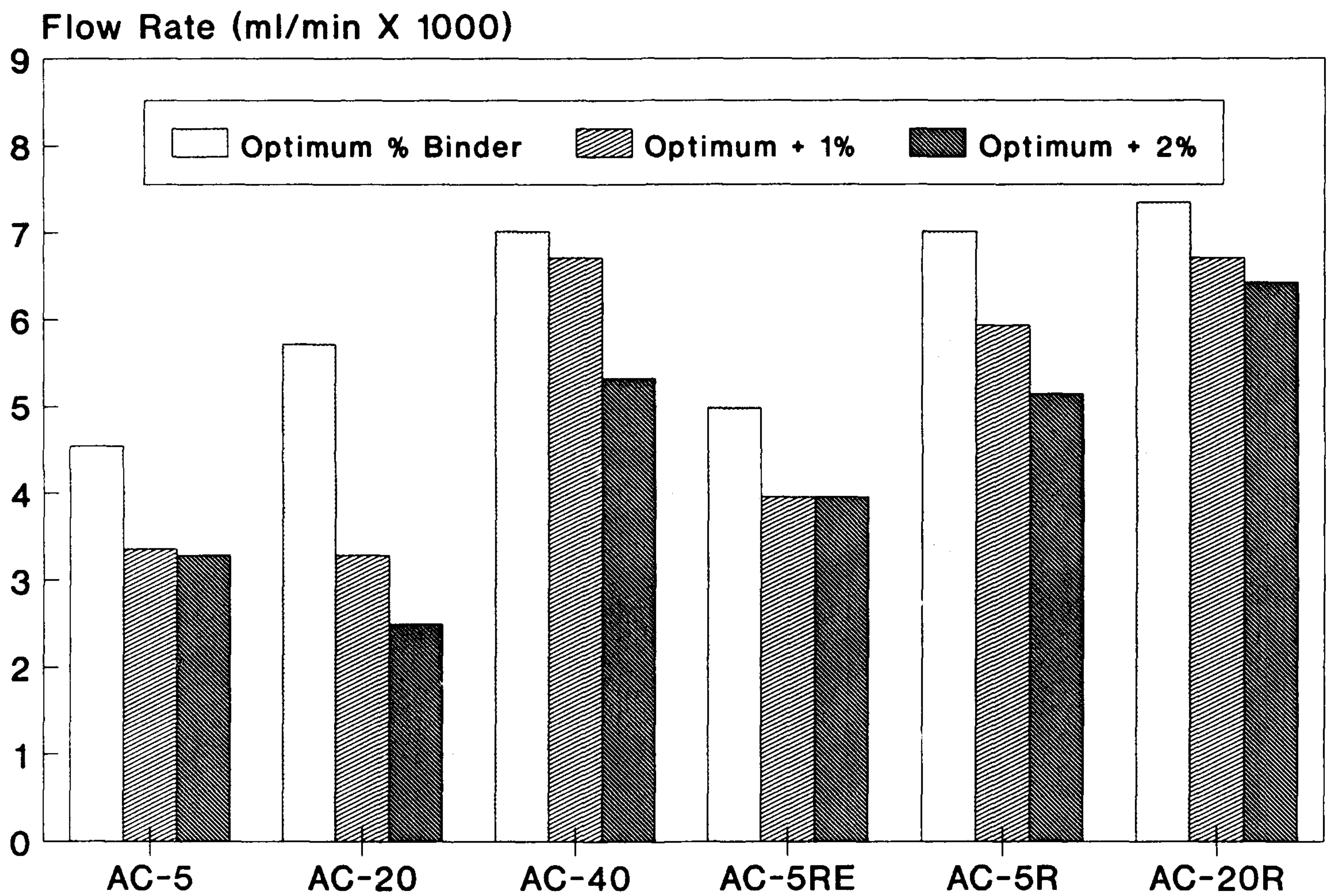

Figure 43. Bar graph of permeability test results

was used in measuring field permeability flow rate values which reportedly ranged from 0 to 4800 ml/min. The pavements investigated by White (1976) ranged from improperly constructed and unfunctional to fully functional PFC pavements.

96. Figure 42 shows the relationship between permeability and binder content for each of the test binders. The AC-5 and AC-20 samples had the lowest flow rate values of the test group, and the AC-5R and AC-20R samples had the highest flow rate values of the test group. The AC-40 test results were substantially higher in permeability than those of the other two asphalt cement mixtures, and slightly higher than the AC-5RE results in the 8.0 to 8.6 percent binder range. The same data are presented in a different fashion in Figure 43. Keeping in mind that the OBC's for the asphalt rubber mixtures are 1.4 percent higher than those of the asphalt cement mixtures, the bar chart indicates that the addition of rubber to asphalt cement binders can increase the resulting open-graded mixture's permeability by about 10 to 20 percent. The significance of this benefit is increased by the fact that the permeability increase for the asphalt rubber binder mixtures is accomplished with a thicker film of binder. Loss of PFC mixture permeability from higher than OBC's is also reduced when using asphalt rubber binders.

Stripping

97. The ASTM stripping test was conducted on the asphalt cement and open-graded mixtures using the same three binder contents as used for the other mix tests: 6.6, 7.6, 8.6 percent. This same test was conducted on the asphalt rubber mixtures containing 8.0, 9.0, and 10.0 percent binder. All asphalt cement and asphalt rubber mixtures passed the 95 percent binder retention criteria specified by the ASTM standard. As mentioned previously in Part III, the stripping test is known to identify only those binder and aggregate mixtures with a serious stripping potential. Since the granite aggregates used in these tests had no history of stripping in field applications, these test results were not surprising.

98. The Texas Boiling Test was used in this study to measure stripping potential under more severe conditions than those of the ASTM stripping test. The binder and aggregate mixtures were tested at OBC's (6.6 percent for the

asphalt cement samples and 8.0 percent for the asphalt rubber samples) since previous test results supported these binder contents as the optimum values for their respective open-graded mixtures. Two observers were allowed to make independent determinations of the visually-obtained test results. These independently determined test results were nearly identical for all test samples and the averages of these values are given in Table 11.

Table 11

Texas Boiling Test Results

Binder	AC-5	AC-20	AC-40	AC-5RE	AC-5R	AC-20R
Percent Retained Binder	60	70	70	75	80	90

These test results indicate that the increased viscosity and tackiness of the asphalt rubber binders can reduce the stripping potential of PFC mixtures under severe conditions. Part of the advantage given to the asphalt rubber mixtures is due to the higher binder contents which result in thicker binder films on the aggregates. Additional binder retention with increased binder viscosity is also evident in these test results.

99. The Porewater Pressure Debonding Test was conducted on open-graded mixture samples blended with the OBC for each test binder as was the Texas Boiling Test. This test was used to measure each mixture loss in tensile strength resulting from stripping under porewater pressure conditions. The percent retained strength value is used to measure this strength loss. A higher percent retained strength by this test indicates a greater resistance to stripping resulting from excessive porewater pressures. A minimum strength retention value of 70 percent is used to identify open-graded mixtures which are sufficiently resistant to stripping under the conditions of this test.

100. The results of the porewater pressure debonding tests, as shown in Table 12, indicate that the AC-5R and AC-20R binders provided maximum resistance to stripping resulting from repeated porewater pressures. The AC-5 mixture had about 10 percent less retained strength, with the AC-5RE and AC-40 mixtures resulting in an additional 4 percent reduction in retained strength.

The poorest performer in this test was the AC-20 mixture which lost 21 percent of its tensile strength after repeated porewater pressure conditioning. The tensile strength values seemed to group together according to their base asphalt cement viscosity grade. The significance of these strength values in themselves is unknown since PFC's typically do not have any mixture strength requirements.

Table 12

Porewater Pressure Debonding Test Results

PFC Binder	Dry Strength psi	Wet Strength psi	Retained Strength percent
AC-5	16.9	15.0	89
AC-20	38.5	30.6	79
AC-40	56.1	47.9	85
AC-5RE	7.3	6.2	85
AC-5R	9.6	9.4	98
AC-20R	18.5	18.3	99

PART VIII: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

101. This laboratory study was conducted to evaluate the effectiveness of using asphalt rubber binders in PFC pavements. This research program consisted of a review of available literature and existing data, and a three-phase laboratory study on various grades of binders and open-graded mixture specimens. Conventional and state-of-the-art test methods and equipment were used to evaluate the binders and PFC mixture specimens. The objective of this research was to determine the potential benefits of asphalt rubber binders when used in PFC's and to recommend the asphalt rubber types and mix design procedure required to achieve optimum field performance.

102. The review of the pertinent literature and existing data indicated that asphalt rubber binders had been used in a limited number of PFC field applications, but these applications were relatively few and geographically widespread in the United States. Several research studies conducted by federal and state transportation agencies had indicated a number of potential benefits in using asphalt rubber binders, but most of these studies concluded that further research was needed to properly design asphalt rubber paving mixtures. Several reports of field applications and applied research programs were documented by European countries and other international pavement researchers. The international experience was much the same as that found in the United States: asphalt rubber PFC's seem promising but are not widely used. In general, the literature indicated that experience with asphalt rubber binders is limited and that most agencies who recognize the potential benefits of using these binders are waiting for technical support before using asphalt rubber in their pavement systems.

103. The test binders used in all of the tests of this study included three unmodified asphalt cements and three asphalt rubber binders. A low, medium, and high viscosity binder was represented in the asphalt cement group as well as the asphalt rubber binders. The asphalt cements used in this study included an AC-5, AC-20, and AC-40 grade. All of the asphalt rubber binders contained the same ground rubber which had been reclaimed from waste tires. The AC-5 asphalt cement was blended with 16 percent rubber and 5 percent

extender oil to make the test binder labeled AC-5RE. The same AC-5 asphalt cement was blended with 17 percent rubber and the resulting binder was labeled AC-5R. The last asphalt rubber binder used in this study was made by blending the AC-20 asphalt cement with 17 percent rubber and the resulting binder was labeled AC-20R.

104. The first phase of this laboratory study evaluated the physical properties of the six test binders. Most of these binder tests were industry standards used to classify and specify traditional asphalt cements. These tests included the kinematic, absolute, Brookfield, and Haake viscosity tests; the needle and cone penetration tests; the ductility test; the ring and ball softening point test; and the resiliency test, which is a common method of evaluating the elastic resilience of pavement joint sealant materials.

105. By comparing the Phase I test results of the asphalt rubber binders to the test results of the asphalt cements, several performance predictions were formulated. The viscosity tests indicated that the asphalt rubber binders tend to be less temperature susceptible and that higher than normal mixing and compaction temperatures would likely be necessary to handle these highly viscous binders. Both penetration tests supported the conclusion that asphalt rubber binders offer reduced temperature susceptibility across a wide range of typical pavement service temperatures. The ductility test proved to be unsuitable for testing asphalt rubber binders, thereby allowing no comparative analysis. The softening point test results strongly suggested that the addition of rubber to asphalt cement would significantly reduce the chances of a PFC becoming tender and unstable in warm climates. The resiliency test highlighted the superior elastic properties of the asphalt rubber binders, indicating improved pavement durability and elastic recovery potential.

106. The second phase of the laboratory study was designed to evaluate the effects of several types of aging on the test binders. The thin film oven test was used to simulate the binder aging process caused by the heating, storage, and mixing temperatures encountered at an asphalt plant. The weatherometer was used to simulate both short- and long-term aging caused by the environment once the binder is in the PFC. The weatherometer exposed samples to cycles of ultraviolet radiation and water spray with constant heat to simulate environmental aging. Once aged, the binders were tested using

three of the Phase I binder tests: absolute viscosity, needle penetration, and the softening point test. A weight loss caused by the aging process was also determined.

107. The aged viscosity tests conducted during Phase II of this study indicated that the asphalt rubber binders age hardened about 50 percent less than their unmodified asphalt cement counterparts. The AC-5RE showed increased age hardening in the viscosity test, and this was attributed to the evaporation of the extender oil additive. The aged penetration tests supported the implication that asphalt rubber binders are less susceptible to all types of age hardening. No significant change in softening point was measured for any of the test binders under any aging condition. The asphalt rubber binders endured more weight loss as a group when compared to the asphalt cement binders. This was theorized to have been caused by the evaporation of a small amount of petroleum-based oil found in the tire rubber, but the amount of weight loss did not appear to affect significantly the other aging properties.

108. The third and final phase of laboratory tests was focused on mixture tests made on laboratory samples of a typical PFC aggregate gradation combined with each of the six test binders. An evaluation of the current standard method for determining OBC's and a modified version of this test method were made during Phase III tests. This was accomplished by determining OBC's by both methods and using these binder contents in the remaining mix tests. The modified method for determining OBC's allowed for higher than normal binder contents when using asphalt rubber.

109. The Phase III tests began with a mix design analysis where the varying binder contents used with each test binder were evaluated against the resulting open-graded mixture specimen voids and density measurements. A binder drain off test was conducted on these laboratory mixtures to determine plant mix temperature limits in terms of excessive binder drainage in the open-graded mixture before placement. A permeability test was conducted in the laboratory to comparatively analyze the effects of binder type and binder content on the PFC's permeability. Finally, three different stripping tests were conducted to evaluate the stripping potential of each test binder.

110. The tests conducted to determine OBC's resulted in a 6.6 percent optimum for the asphalt cement samples and an 8.0 percent optimum for the

asphalt rubber samples. The mix design analysis indicated that asphalt rubber binders provide higher void contents (thus higher water carrying capacities), even at higher binder contents. The binder drain off test results identified a significant advantage offered by asphalt rubber binders in that they are much less susceptible to detrimental binder drainage, even at higher mixing temperatures. The permeability tests supported the indications of the voids measurements made in the mix design analysis as the asphalt rubber samples had substantially higher permeabilities. The first stripping test, which was specified by ASTM, merely confirmed that the aggregates being used did not have a serious stripping potential. The second stripping test, known as the Texas Boiling Test, indicated slight to moderate improvements in stripping resistance for the asphalt rubber binders. The final stripping test, known as the Porewater Pressure Debonding Test, indicated that the two asphalt rubber binders without extender oil provided outstanding resistance to the stripping effects of porewater pressures. The asphalt rubber binder with extender oil rated moderately lower along with the other test samples in this stripping test.

Conclusions

111. Based on the results of this study which included the literature review and three-phase laboratory study, the following conclusions were made on the effectiveness of using asphalt rubber binders in PFC pavements:

- a. The addition of 16 to 17 percent ground reclaimed rubber to an asphalt cement will increase the binder viscosity by 100 to 2,000 percent, depending upon the test method and test temperature.

- b. Differing grades of asphalt rubber binders produced with similar dosage levels of the same rubber have very similar viscosities above 200°F. This indicates that above about 200°F, the viscosity of the binder is controlled by the rubber, and below 200°F, the base asphalt cement has a significant influence on binder viscosity.

- c. The addition of reclaimed rubber improved low-temperature binder properties and reduced overall temperature susceptibilities as indicated by the penetration tests.

d. The ductility test is unsuitable for testing the type of asphalt rubber binders represented in this study.

e. Softening points are increased by approximately 20 to 30°F by the addition of 16 to 17 percent reclaimed rubber. This means that asphalt rubber PFC's should be less susceptible to traffic-induced deformation distresses at high pavement temperatures.

f. Asphalt rubber binders have higher elastic recovery potentials than unmodified asphalt cement binders.

g. Asphalt rubber binders harden 50 percent less than asphalt cement binders when aged by the thin film oven test. This means that the viscous properties of asphalt rubber binders would be much more stable at the asphalt mixing plant. The exception to this is when an extender oil is added with the rubber to the asphalt cement, as a significant portion of extender oil will vaporize at normal plant temperatures, causing sizeable increases in binder viscosity.

h. Environmental age hardening is reduced by the addition of reclaimed rubber. The exception to this statement again is when an extender oil is added with the rubber. Enough extender oil was lost during the weatherometer aging process to cause comparatively higher age-hardening tendencies for the AC-5RE test binder.

i. The penetration test evaluation of the aged binders supported the conclusions reached by the aged viscosity analysis. Detrimental binder aging effects were reduced for the asphalt rubber binders, except when an extender oil was used with the rubber addition.

j. Softening points of the asphalt cement and asphalt rubber binders were relatively unchanged by the laboratory aging processes used in this study.

k. Asphalt rubber binders had higher weight losses after thin film oven test aging when compared to the asphalt cement binders, but the amount of weight loss did not appear to affect significantly other aging properties.

l. The current method of determining OBC's for PFC's was modified to allow for higher binder contents when using asphalt rubber binders. This modified method resulted in an OBC for the asphalt rubber mixtures which was 1.4 percent higher than the optimum derived for the asphalt cement binders. Both of these OBC's were verified by the Phase III mix tests.

m. Open-graded mixture samples made with asphalt rubber binders had void contents about 3 to 8 percent higher than their asphalt cement counterparts, depending upon the binder content used. The percent voids filled with binder was reduced and the unit weight was increased by the addition of reclaimed rubber in open-graded asphalt mixtures.

n. Binder drainage at typical asphalt plant mixing temperatures was significantly reduced by the addition of reclaimed rubber to the asphalt cement. This means that asphalt rubber PFC mixtures can be produced at higher temperatures, thereby allowing construction to occur in colder climates.

o. The permeability of a PFC is increased when using asphalt rubber binders, making the asphalt rubber PFC more effective in draining rainwater.

p. Stripping of the binder from aggregates caused by the presence of water and porewater pressures was reduced for the asphalt rubber test samples. However, one of the stripping tests indicated that the AC-5RE binder did not enhance stripping resistance.

q. All laboratory test results indicated that asphalt rubber PFC's would be more durable, longer lasting, and better water draining pavement layers when compared with unmodified asphalt cement PFC's. These pavement performance improvements are due to the inherent physical and chemical properties of the asphalt rubber binders and to the fact that a thicker binder film thickness on the aggregate can be achieved with the asphalt rubber. However, the addition of extender oil to the AC-5 asphalt and rubber blend seemed to affect detrimentally some of the test results, especially the aging properties.

Recommendations

112. Based on the conclusions derived from the results of this laboratory study, the following recommendations were made:

a. Asphalt rubber binders should be used in PFC's to achieve any or all of the following pavement performance improvements:

(1) Reduced temperature susceptibility.

(2) Reduced low temperature cracking potential.

(3) Reduced high temperature deformation distress potential.

(4) Reduced age hardening from plant mixing temperatures and from exposure to the environment.

(5) Increased permeability for improved water draining capabilities.

(6) Reduced binder drainage at high plant mixing and hauling temperatures.

(7) Reduced stripping potential.

b. Any asphalt cement grade between the AC-5 and AC-20 viscosity grades may be used in the production of asphalt rubber binders. A good rule of thumb to follow in selecting the proper grade of asphalt cement is to use one grade lower than what is normally used. For instance, if an AC-20 is normally specified, then an AC-10 with rubber may be substituted. The use of extender oils with these binders will reduce viscosity, but may detrimentally affect the aging properties and other benefits achieved by the addition of reclaimed rubber.

c. The mixing temperature of an asphalt rubber PFC mixture should be between 275°F and 325°F. Higher viscosity asphalt rubber binders will normally require higher mixing temperatures. Colder ambient temperatures during construction or longer haul distances between the asphalt plant and construction site may also require mixing temperatures in the upper end of this recommended range.

d. Although the type and dosage level of reclaimed rubber used in this study is representative of the current technology, additional research needs to be conducted to evaluate the effects of different rubber reclaiming processes and dosage levels in the binder.

e. Field investigations should be conducted to verify the pavement performance predictions developed in this study.

f. The generalized mix design method found in Appendix A of this report should be used when designing asphalt rubber PFC's in the future and verified by these field applications as an appropriate design procedure.

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APPENDIX A: ASPHALT RUBBER POROUS FRICTION COURSE MIX DESIGN METHOD

ASPHALT RUBBER PFC MIX DESIGN METHOD

Introduction

1. This mix design guidance outlines the modifications required of the current standard PFC mix design method when using asphalt rubber binders. The current standard mix design method is documented by the Federal Highway Administration Report No. FHWA RD-74-2. The new mix design method involves a modification of the equation used to determine OBC and the addition of a simple laboratory test used to validate the OBC and plant mix temperature.

Procedure

2. Select an aggregate source and gradation which meets all standard requirements for PFC mixtures.

3. Determine the surface constant (K_c) value according to the standard California Kerosene Equivalency test method as prescribed in FHWA RD-74-2.

4. Use the surface constant (K_c) value in the following equation to estimate the optimum binder content (OBC):

$$OBC = \frac{(2.0 \times K_c) + 4.0}{1 - \text{percent rubber}}$$

where percent rubber = percent of rubber by weight in the asphalt rubber binder

5. Prepare three 300 g mixtures of the aggregate mixture to be used in the project. This aggregate sample should have the same gradation as that specified in the project specifications.

6. Mix the aggregate samples with the asphalt rubber binder at temperatures representative of plant mixing conditions. Use the OBC estimated in step 4*.

7. Spread each freshly-coated mix sample evenly over the center area (approximately 6 in. in diameter) of a 1 ft sq pyrex glass plate. Use separate glass plates for each sample.

8. Place these samples in an oven which has been preheated to the selected plant mix temperature.

9. Remove the samples from the oven after 2 hr and allow them to cool to room temperature.

10. After the samples have cooled, observe the bottom of the glass plates and visually determine the percentage of the 6-in. diam sample area which is covered with drained binder. Record this percentage drainage value (in increments of 10 percent) as the sample test result and use an average of the three sample tests as the final test result.

11. If the percent drainage value measured by this test is more than 50 percent, then excess binder drainage may occur in the mix before placement. To eliminate this potential problem, reduce the plant mix temperature or binder content and repeat steps 5 through 10 until a percent drainage value of 50 percent or less is obtained.

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* Multiple plant mix temperatures may be evaluated with this test by using varying oven temperatures. Multiple binder contents also may be evaluated by using varying binder contents in the test samples.

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